Faculté environnement naturel, architectural et construit - ENAC

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Test Report MCS 23.09.01-part 3

Bending fatigue test of R-UHPFRC – RC composite beams

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1 Objectives

The experimental campaign was intended to study the bending fatigue behaviour of reinforced UHPFRC (R-UHPFRC) – reinforced concrete (RC) composite member (RU-RC member). The test results were expected to be utilised for determination of fatigue endurance limit of RU-RC member, proposal of fatigue design rules for RU-RC member and development of a numerical model to describe the bending fatigue behaviour of RU-RC member.

2 Specimens, test set-up and instrumentation

2.1 Material

The mix of UHPFRC used in experimental tests is HIFCOM 13 developed by MCS, EPFL. This mix is characterised by 3.0 vol.- % content of 13 mm long steel fibres with a diameter of 0.16 mm and by the use of CEM III/B type cement which contains a high percentage of blast furnace slag (66%~80%) (Table 1). Six prisms with section of 40 mm × 40 mm and length of 160 mm were produced with the same UHPFRC as used for the fabrication of RU-RC beam specimens. Three of those prisms were tested 56 days after casting and the average compressive strength and modulus of elasticity were 219.6 MPa and 47.3 GPa each (Table 2). The other three prisms were tested 194 days after casting and the average compressive strength and modulus of elasticity were 246.5 MPa and 49.8 GPa, respectively (Table 2).

Concrete in the RC part was C30/37 grade with a maximum aggregate size of 16 mm. Three cylinders with diameter of 110 mm and height of 220 mm were produced with concrete used for the fabrication of RU-RC beam specimens. Those cylinders were tested 207 days after casting and the average compressive strength was 64.5 MPa (Table 3).

Steel rebars arranged in the UHPFRC layer and the RC part were of B500B grade and had a nominal yielding strength of 500 MPa.

Table 1 Composition of UHPFRC mix "HIFCOM 13"

Component	Type	Mass [kg/m^3]	Remarks
Cement	CEM III/B	1277.4	
Silica fume	Elkem Microsilica 971 U	95.8	7.5 % of cement mass
Sand	Quartz sand MN 30	664.6	d_{max}<0.5 mm
Steel fibres	Bekaert OL 13/0.16 mm	235.5	3.0 vol.-%, brass coating
Superplasticiser	Sikament P5	42.3	3.3 % of cement mass
Water		198.0	W/C=0.155

Table 2 Test results of UHPFRC prisms 40mm × 40mm × 160mm fabricated on 15.04.2010

Report No.	ID No.	Age [days]	Compressive Strength [MPa]	Modulus of Elasticity [GPa]	Modulus of Rupture [MPa]
129/10/LMC 130/10/LMC	1167	56	223.8	48.5	52.4
	1168		216.3	46.5	35.6
	1169		218.8	47.0	34.9
	Average		219.6	47.3	40.9
306/10/LMC 307/10/LMC	2011	194	243.1	49.0	46.4
	2012		243.8	49.0	42.6
	2013		252.5	51.5	49.2
	Average		246.4	49.8	46.0

Table 3 Test results of concrete cylinders ϕ110mm × 220mm fabricated on 12.03.2010

Report No.	ID No.	Age [days]	Compressive Strength [MPa]	Modulus of Elasticity [GPa]
264/10/LMC	1872	207	64.0	35.0
	1873		64.5	36.5
	1874		64.9	35.5
	Average		64.6	35.6

2.2 Specimen

The specimen is a 1,900 mm long slab-like beam with a cross section of 400 mm × 220 mm (Fig. 1). Thickness of R-UHPFRC layer is 50 mm. The RC part was first cast, and 28 days after that the UHPFRC layer was cast on the top surface of the RC part which was roughened with hydro-jetting to obtain monolithic bond between UHPFRC and concrete (Fig. 2). Neither any adhesion products nor any shear connector was used for the bonding. Both UHPFRC and concrete were cast in one day using material mixed in a few batches. Specimens were cured under constant climate condition for more than 75 days.

Four steel rebars of 16 mm and 10 mm diameter were arranged longitudinally in the top and bottom of the RC part with a spacing of 100 mm. Four steel rebars of 10 mm diameter were arranged in the UHPFRC layer with a spacing of 100 mm. The RC part had 8-mm diameter two-legged closed stirrups for assembly of longitudinal steel rebars.

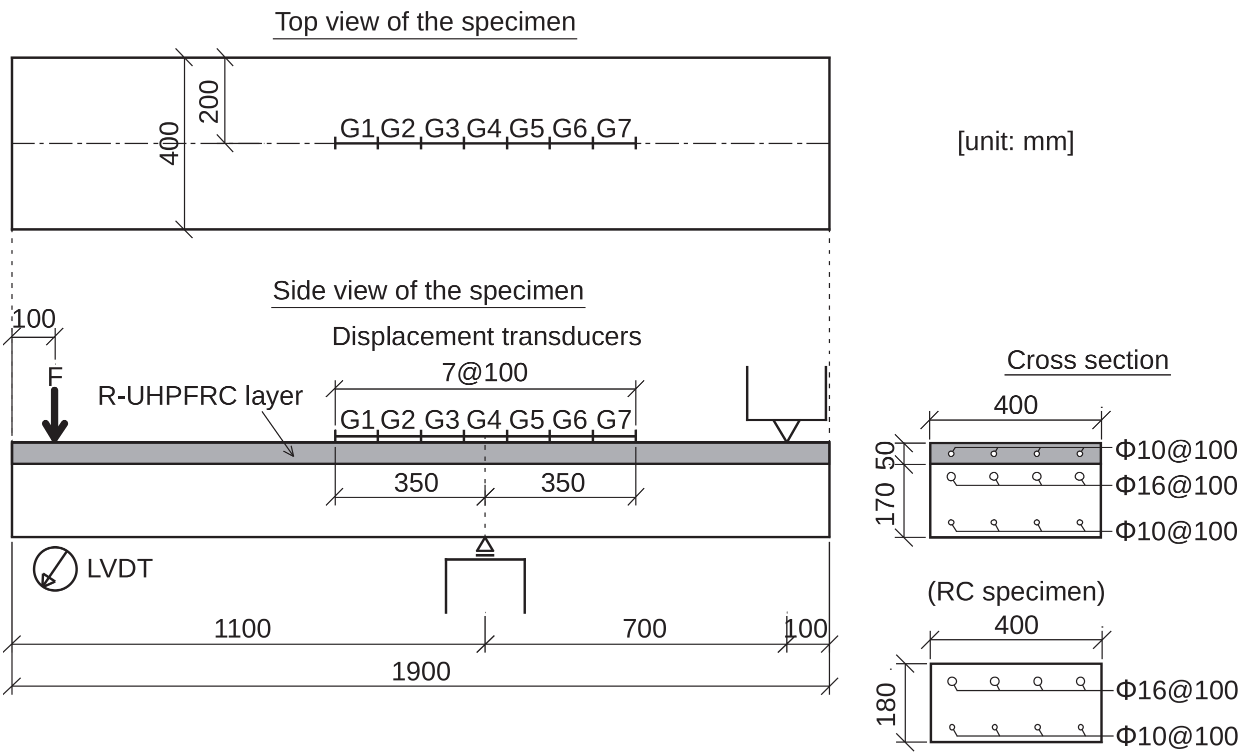


Figure 1 Specimen geometry and measuring devices

(a) (b)

Figure 2 Specimens just before casting (a) concrete and (b) UHPFRC

2.3 Test set-up

Cantilever was used as static system, representing a strip of RC bridge deck cantilever improved with R-UHPFRC (circled part in Fig. 3). Fig. 4 shows the test rigs and steel frame for the test set-up with an RU-RC beam placed with its R-UHPFRC layer of the top. Cyclic force was imposed at the end of the specimen by the hydraulic jack in force control and negative bending moment was caused on the specimen, where the R-UHPFRC layer was subjected to tension. Sinusoidal cyclic force was controlled by Amsler hydraulic actuator. Since the Amsler hydraulic actuator didn't monitor force level, a load cell installed between the jack and the specimen was used for monitoring the force level.

The movable and supplementary supports were placed on massive concrete blocks. The fixed support was attached to a steel frame. The supplementary support was used when the specimens were set on the test set-up. The fixed and supplementary supports were put on the top and bottom of the specimen at the end of the specimen and the movable support was put at a distance of 800 mm from the fixed support.

Every small space between the test rigs was removed as much as possible because small space can make large oscillation during fatigue test, leading to instability of the whole test set-up.

Steel plates of 200 mm × 400 mm × 20 mm were put on the positions where force was applied to the specimen in order to distribute the force over all width of the specimen.

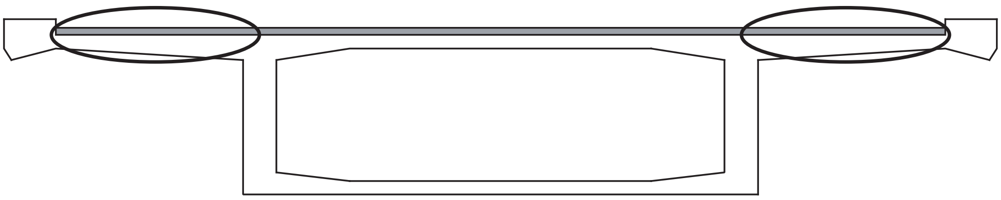


Figure 3 RC bridge deck slab improved with R-UHPFRC layer

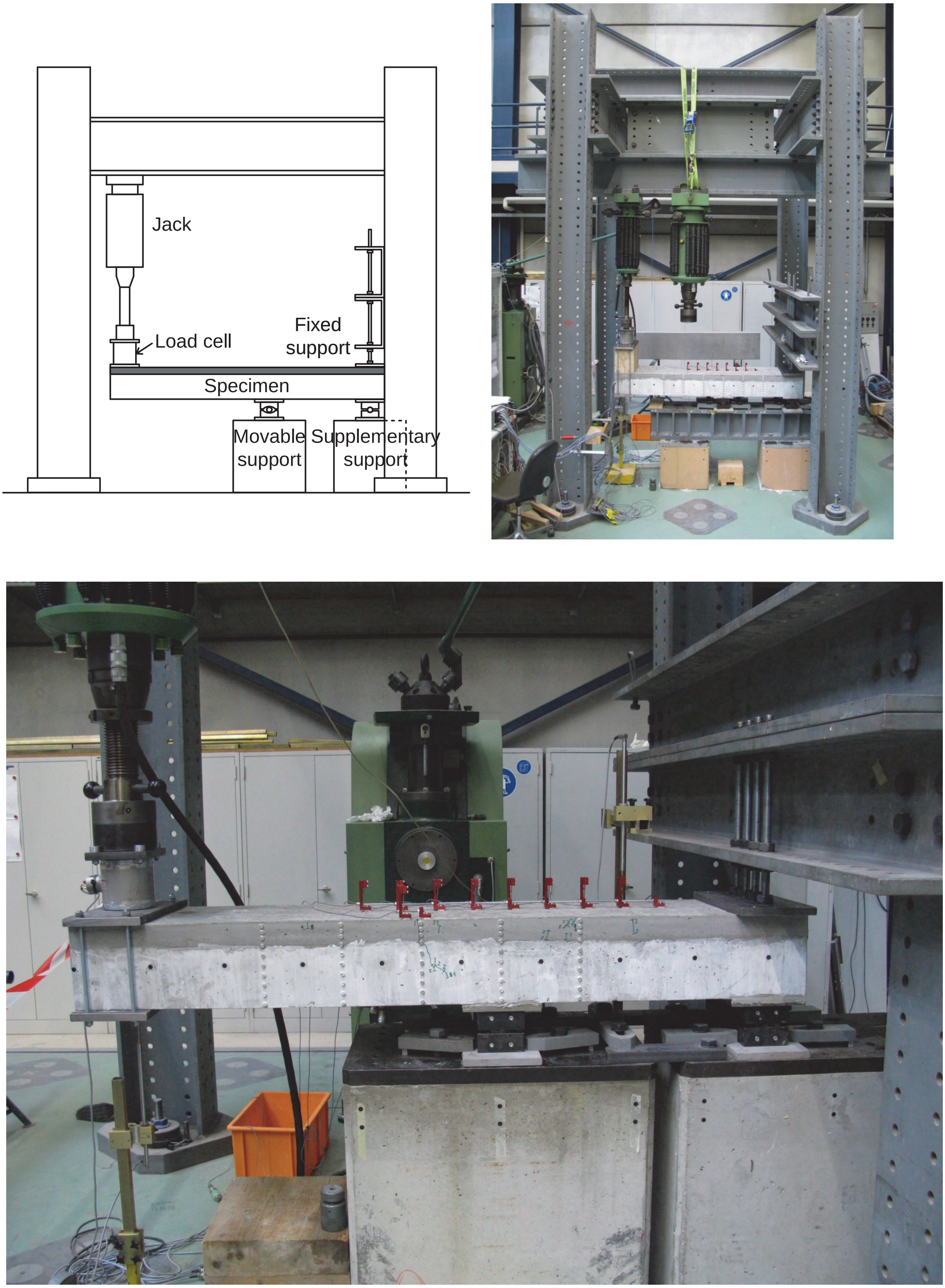


Figure 4 Test set-up

2.4 Measuring Devices

Linear Variable Differential Transducer (LVDT) was set up to measure the specimen deflection at the position of the jack (Fig. 1). Seven displacement transducers with a base length of 100 mm were set up at the transversal centre of the top surface of the R-UHPFRC layer to measure the R-UHPFRC deformation (Fig. 1). The displacement transducers were intended to cover the area where the largest negative bending moment acted. Load cell was installed just below the force applying jack to measure the force.

Deformation over the entire depth of the specimen was measured manually at selected fatigue cycles, during which the deflection was kept constant by applying the specified maximum fatigue force. The manual measurements were taken with a hand-held deformeter. The gauge was used to measure the deformation on the surface of the concrete and UHPFRC between metal targets glued on to the side of the beam (Fig. 5). Seven metal targets were put evenly over the RC part with spacing of 25 mm and three targets over the R-UHPFRC layer with spacing of 15 mm. There were five columns for the deformation measurements and each column had a base length of 200 mm. These metal targets were intended to cover the area where the largest negative bending moment acted.

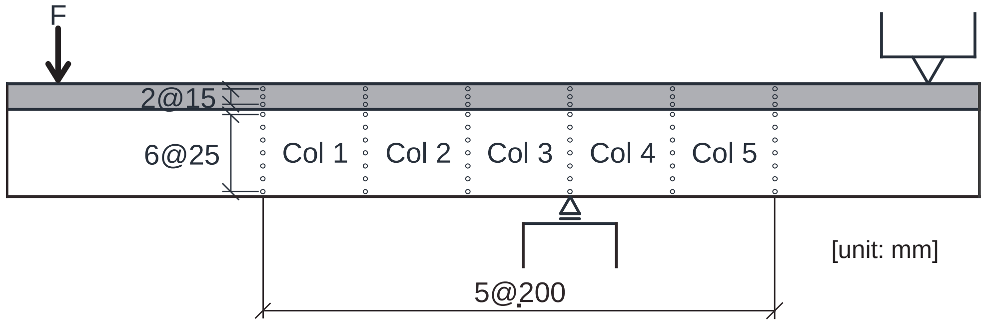


Figure 5 Position of metal targets

3 Testing program

3.1 Static test

Static bending test was conducted to understand the static specimen behaviour as well as the ultimate static strength. Static force was applied manually in 10 kN increments. Tracing of crack pattern and measuring of deformation over the entire depth of the specimen were conducted every 10 kN. The test was continued until the specimen lost force bearing capacity completely. Specimen deflection, deformation of R-UHPFRC layer and force were recorded with a frequency of 10 Hz.

3.2 Fatigue test

Bending fatigue tests were conducted with five RU-RC specimens and one RC specimen. Maximum fatigue force F_{max} was varied between 40 % and 60 % of the ultimate static strength F_u determined from the static test. This is based on the findings that the fatigue endurance limit of reinforced concrete beam subjected to bending fatigue is 50 % of the ultimate static strength [1]. Minimum fatigue force F_{min} was always 10 % of maximum fatigue force. When a specimen sustained more than 10 million fatigue cycles, the test was regarded as "run-out" and the new fatigue test was continued at a higher fatigue force level.

Bending fatigue test of RC specimen was intended to investigate the difference of behaviour with RU-RC specimen. The maximum fatigue force was 50 % of the ultimate static strength determined from calculation. Minimum fatigue force was 10 % of maximum fatigue force.

Fatigue force was applied manually during the first 10 cycles and then sinusoidal fatigue force cycles were imposed at 8 Hz.

Specimen deflection, deformation of R-UHPFRC layer and force were recorded with a frequency of 160 Hz. The initial and final phases of the tests were recorded permanently, while between these phases data was recorded for 1 second every 480 cycles. At selected fatigue cycles, the macrocracks caused on the specimen were traced and deformation over the entire depth of the specimen was measured.

4 Result of static test

Although test set-up was planned to cause the specimen to fail in bending, the specimen failed in shear at the span between two supports, not cantilever span (Fig. 6a). When force reached 90 kN, force application was stopped, and just before starting tracing of crack pattern and measuring of deformation over the entire depth of the specimen, the specimen suddenly lost its force bearing capacity and the force dropped (Fig. 6b). This is because a diagonal shear crack was caused at 90 kN, running from movable support with an angle of about 20˚ against horizontal line toward fixed support (Fig. 6a). Thus the ultimate static strength F_u of the specimen was determined to be 90 kN for this test set-up.

Deformation of the R-UHPFRC at G3 zone was by far the largest among all the deformations. Cracks just under the base of G3 displacement transducer might have led to such excessive deformation readings, which was confirmed by observation of macrocrack at pause of the test when applied force reached 70 kN.

Theoretically, distribution of R-UHPFRC deformation readings obtained from seven displacement transducers must follow distribution of bending moment; however, it didn't (Fig. 8). Except G3 zone, deformation readings at G1 zone instead of G4 zone was the largest during the quasi-static bending test (Fig. 6d). This might be due to variation in material property and difference of eigenstresses in the UHPFRC induced by restrained shrinkage.

Fig. 7 shows strain evolution on the side of the beam at column 3. Constant strain growth after 40 kN is observed.

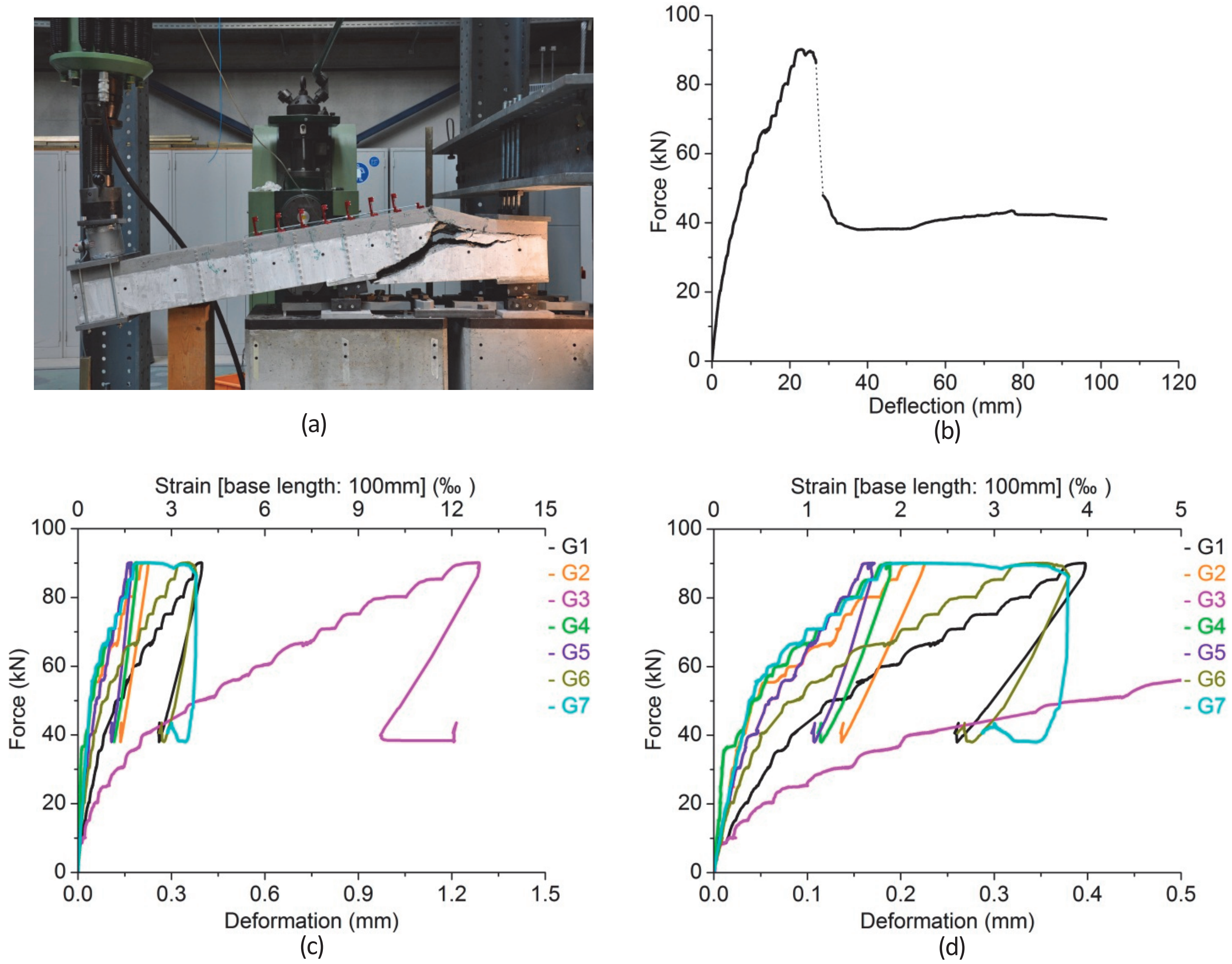


Figure 6 Static test: (a) fractured specimen, (b) force-deflection curve, (c) force-deformation curve of R-UHPFRC and (d) magnified view of force-deformation curve of R-UHPFRC

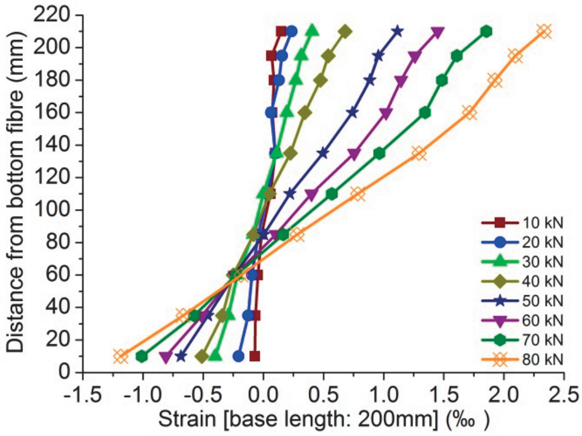


Figure 7 Growth of maximum strain at column 3 over the entire depth of the specimen

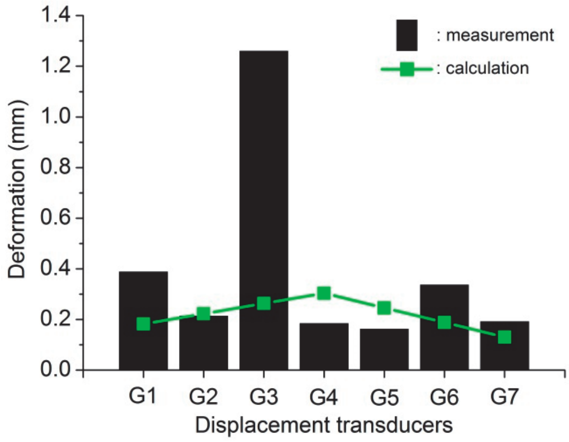


Figure 8 Distribution of deformation of the R-UHPFRC layer at 90 kN

Cracking behaviour and failure mode of static test specimen

<u>0 kN:</u>

[Side of RU-RC beam]

- A horizontal crack was initially observed on the R-UHPFRC – RC interface, extending from G5 to G7 zone.

<u>10 to 40 kN:</u>

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

- No cracks appeared until 40 kN.

<u>50 kN:</u>

[Side of RU-RC beam]

- Two approximately vertical cracks developed crossing the R-UHPFRC – RC interface: one at G3 zone and another at G5 zone.

<u>60 kN:</u>

[Side of RU-RC beam]

- An existing crack at G5 zone increased its length into the RC part.

<u>70 kN:</u>

[Top surface of R-UHPFRC layer]

- Two cracks perpendicular to the longitudinal axis of the beam developed, and one of them was caused below the base of G3 displacement transducer.

[Side of RU-RC beam]

- A short vertical crack appeared crossing the R-UHPFRC – RC interface at outside of G1 zone.
- Two vertical cracks developed: one at G2 zone in the RC part and another at G6 zone in the R-UHPFRC layer.

75 kN:

[Top surface of R-UHPFRC layer]

- A crack perpendicular to the longitudinal axis of the beam developed on the G1 – G2 zone border.

[Side of RU-RC beam]

- A diagonal crack at an angle of 45˚ from the horizontal axis was caused at G7 zone in the RC part.
- A short vertical crack developed on the G6 – G7 zone border in the upper half of the R-UHPFRC layer.
- Existing cracks increased those lengths; especially a vertical crack at G6 zone grew significantly, propagating into the RC part.

80 kN:

[Top surface of R-UHPFRC layer]

- Three cracks perpendicular to the longitudinal axis of the beam appeared on the same path at G3 zone.

[Side of RU-RC beam]

- A vertical crack developed from the R-UHPFRC – RC interface to the RC part at G4 zone.

85 kN:

[Side of RU-RC beam]

- A horizontal crack was caused on the R-UHPFRC – RC interface from the tip of an existing diagonal crack at outside of G7 zone.
- A short vertical crack developed at just outside of G7 zone in the R-UHPFRC layer.

Failure (90 kN):

[Top surface of R-UHPFRC layer]

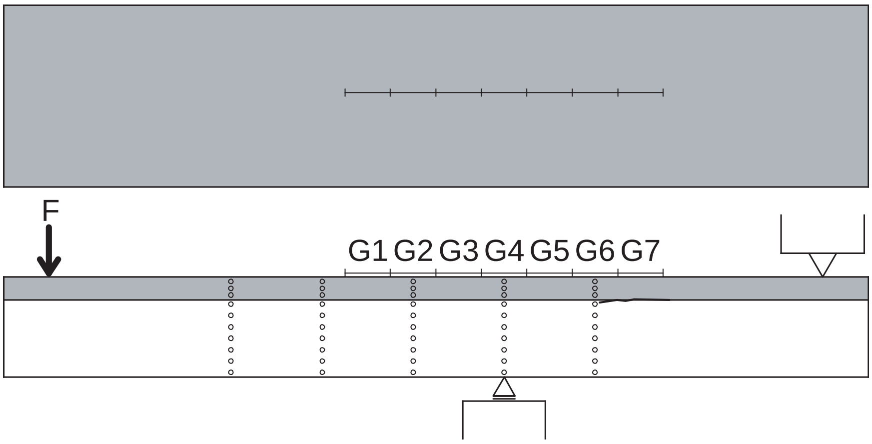
- Fracture crack approximately perpendicular to the longitudinal axis of the beam appeared at outside of G7 zone, connecting to fracture crack on side of the R-UHPFRC layer.

[Side of RU-RC beam]

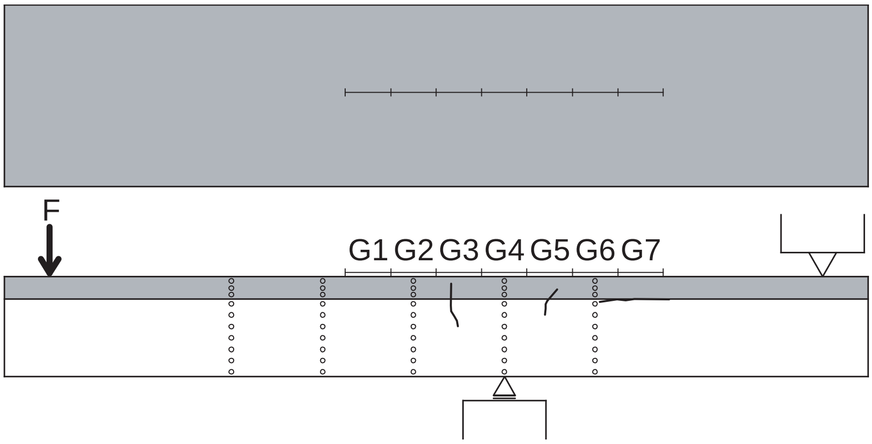
- A diagonal crack at an angle of 20˚ from the horizontal axis developed from the tip of an existing diagonal crack at G7 zone toward movable support.
- The diagonal crack grew toward both movable support and fixed support. All of a sudden its opening mouth got larger and it became fracture crack, while force was being kept at 90 kN. The diagonal fracture crack didn't propagate into the R-UHPFRC layer: when reaching the R-UHPFRC – RC interface, it propagated on the interface to fixed support.
- Vertical fracture crack appeared by increasing the width of an existing crack at outside of G7 zone in the R-UHPFRC layer, connecting to fracture crack on top surface of the R-UHPFRC layer.

Evolution of crack pattern during the static test

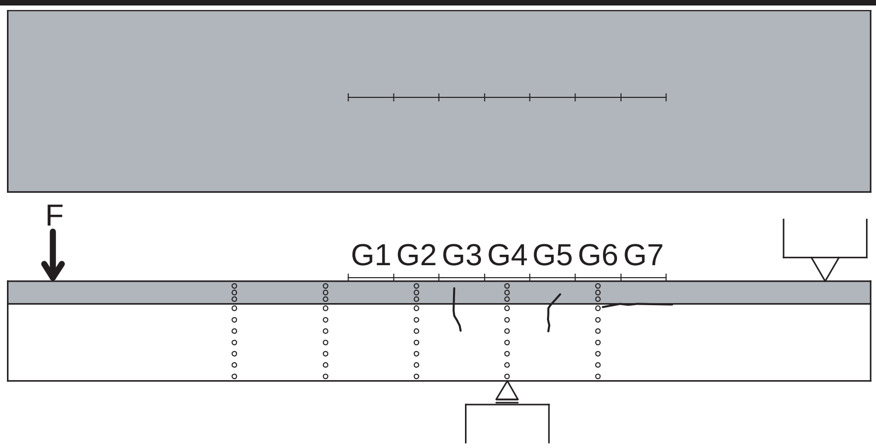
0 kN ~ 40 kN



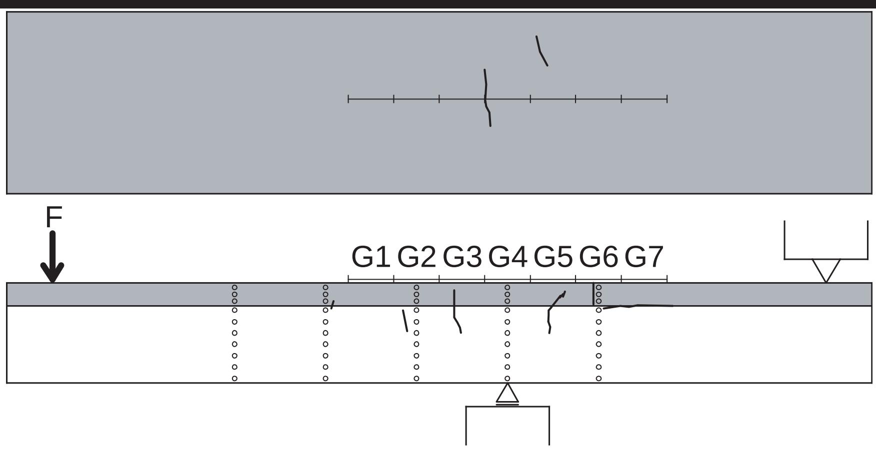
50 kN



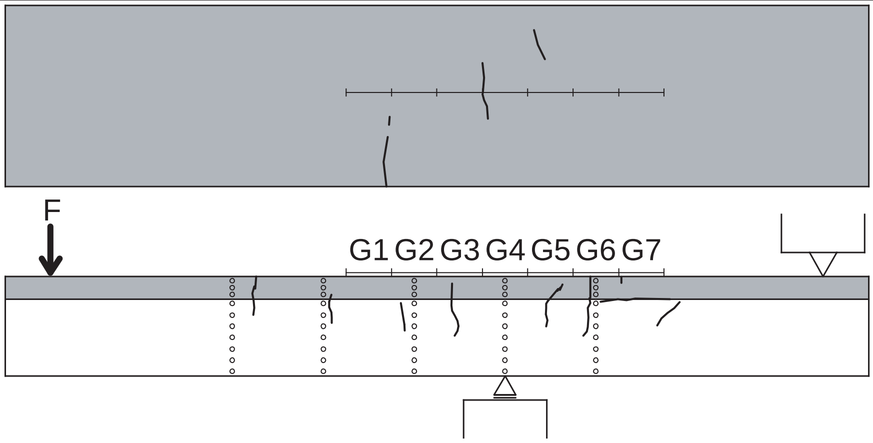
60 kN



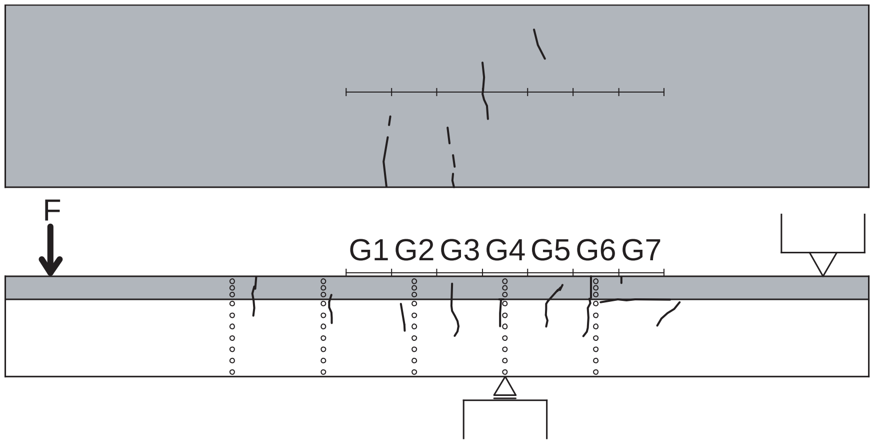
70 kN



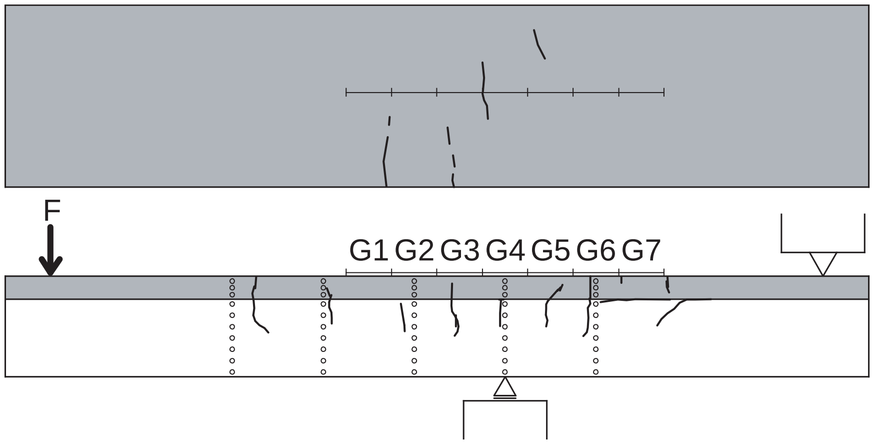
75 kN



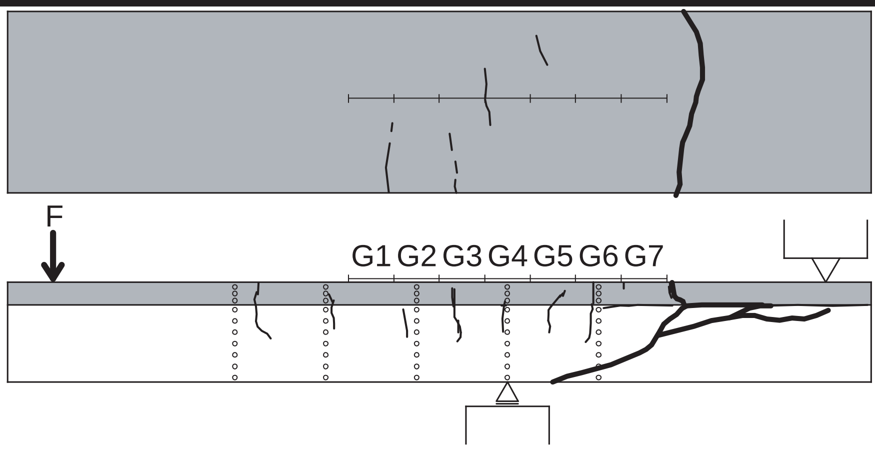
80 kN



85 kN



Failure (90 kN)



5 Results of fatigue tests

Table 4 lists the summary of the bending fatigue test results. When the whole testing system became unstable due to reduction of stiffness of the specimen and force could no longer be applied, the fatigue test was stopped and specimen was regarded as failed. For each test, maximum deflection corresponding to maximum fatigue force, deflection range, maximum deformation of R-UHPFRC layer corresponding to maximum fatigue force and deformation range of R-UHPFRC layer at seven consecutive zones were plotted against the number of fatigue cycles. Since recorded data for each test was huge, reduced number of data (approximately 500 points of data) was plotted for each measurement. In the following, test results are explained one by one.

Table 4 Results of bending fatigue tests of RU-RC beams and RC beam

Test No.		F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N [×10^6]	Remarks
NBF1	i	36.00	3.60	0.40	10.13	run-out
	ii	45.00	4.50	0.50	1.04	
NBF2	i	40.50	4.05	0.45	20.00	run-out
	ii	45.00	4.50	0.50	1.97	
NBF3	i	45.00	4.50	0.50	23.94	run-out
	ii	49.50	4.95	0.55	10.00	run-out
	iii	54.00	5.40	0.60	2.10	
NBF4		49.50	4.95	0.55	6.99	
NBF5		49.50	4.95	0.50	1.00	
RC		25.00	2.50	0.50	0.36	

F_u = 90 kN for RU-RC beam, 50 kN for RC beam

N: sustained number of fatigue cycles

5.1 NBF1 test

First fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
36.00	3.60	0.40	10,133,236	run-out

Behaviour of NBF1 test specimen during the first fatigue test

Deflection:

Maximum deflection rapidly grew until about 700,000 cycles and then its growth rate became low. After that, deflection range kept approximately constant.

Deformation of R-UHPFRC layer:

At all local zones, maximum deformation rapidly grew until about 600,000 to 1 million and then its increasing rate became low. Deformation range at all local zones rapidly grew during the first 200,000 cycles, after which it kept roughly constant until the end of the test.

Deformation over the entire depth of the specimen:

Deformation over the beam depth increased significantly until measurement at 1,015,392 million cycles, after which growht rate of the deformation decreased. Tensile deformation increased at approximately the same rate at every measurement except between 100,601 and 514,523 cycles where tensile deformation growth rate was about five times as high as that of the other measurements. Increase of tensile deformation was larger than that of compressive deformation and neutral axis gradually moved toward compression fibre as the number of cycles increased.

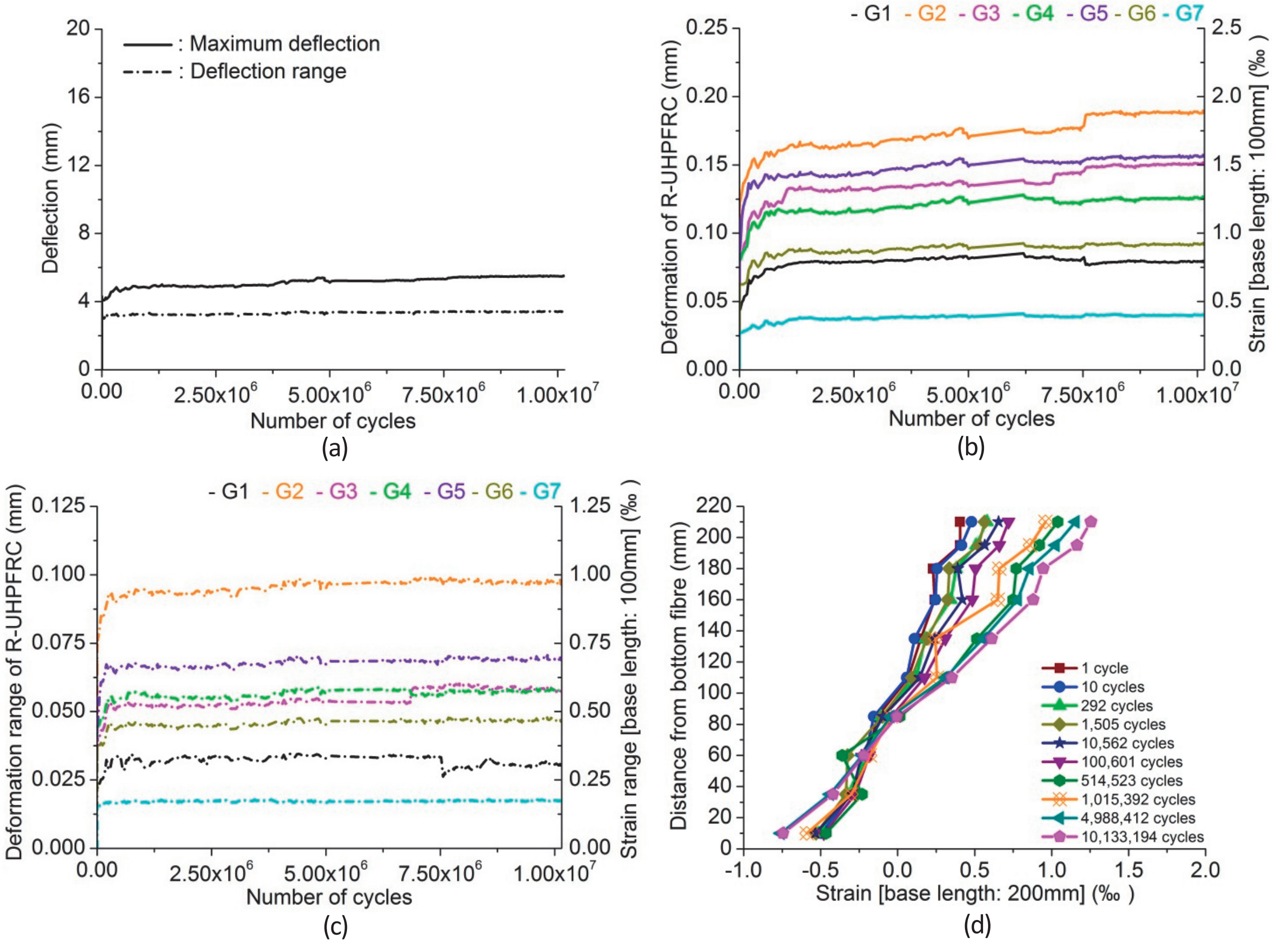


Figure 9 NBF1-i test: growth curves of (a) maximum deflection and deflection range, (b) maximum deformation of R-UHPFRC layer, (c) deformation range of R-UHPFRC layer and (d) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF1 test specimen during the first fatigue test

<u>1 cycle:</u>

[Side of RU-RC beam]

- A vertical crack was caused crossing the R-UHPFRC – RC interface at G3 zone.

<u>292 cycles:</u>

[Side of RU-RC beam]

- A short vertical crack developed at G1 zone in the R-UHPFRC layer, while an existing vertical crack at G3 zone grew.

<u>100,601 cycles:</u>

[Top surface of R-UHPFRC layer]

- A long crack inclined from the transversal axis of the beam with an angle of 5˚ developed at G5 zone.

[Side of RU-RC beam]

- A short vertical crack appeared crossing the R-UHPFRC – RC interface at G6 zone.
- Existing cracks increased those lengths slightly.

<u>514,523 cycles:</u>

[Top surface of R-UHPFRC layer]

- A crack inclined from the transversal axis of the beam with an angle of 5˚ developed at G6 zone.

[Side of RU-RC beam]

- A short vertical crack appeared from the R-UHPFRC – RC interface to the RC part at G5 zone.

<u>1,015,392 to 10,133,194 cycles:</u>

[Top surface of R-UHPFRC layer]

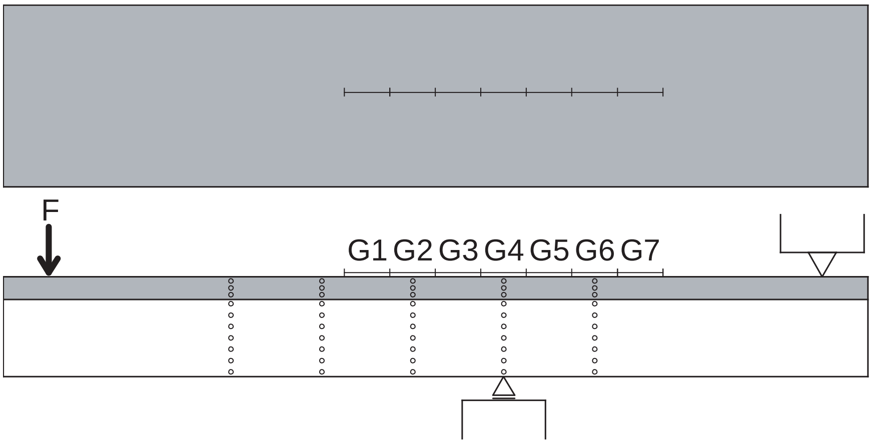
- Some short cracks developed.

[Side of RU-RC beam]

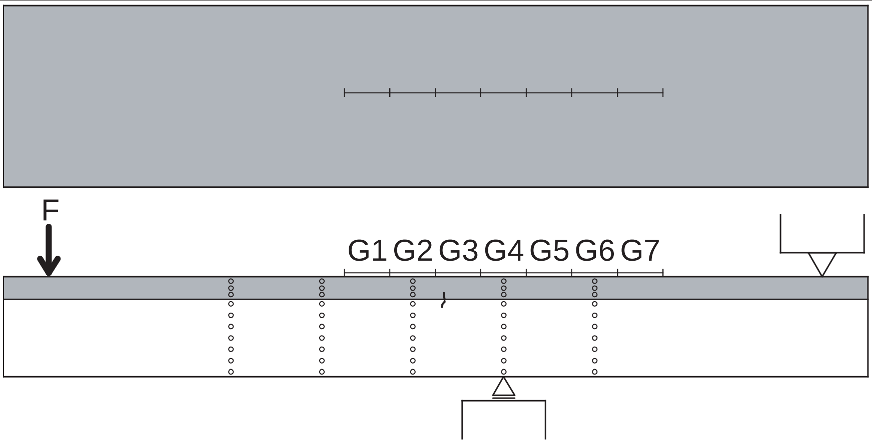
- Significant change wasn't observed on the crack pattern except slight growth of existing cracks.

Evolution of crack pattern on NBF1 test specimen during the first fatigue test

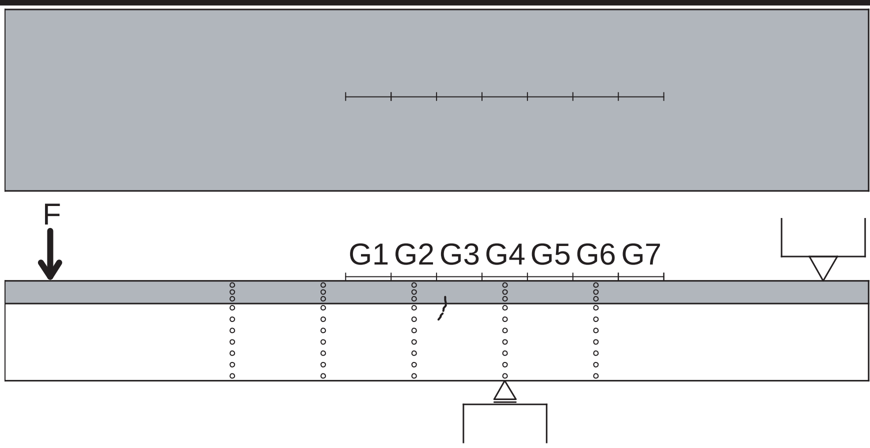
0 cycle



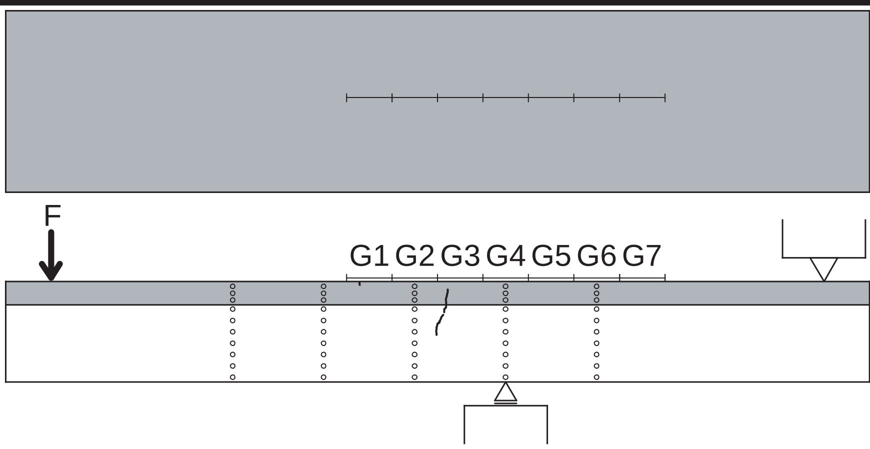
1 cycle



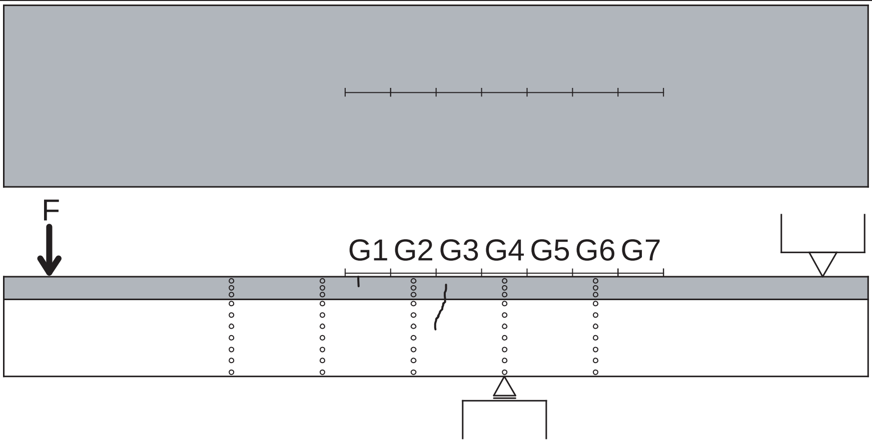
10 cycles



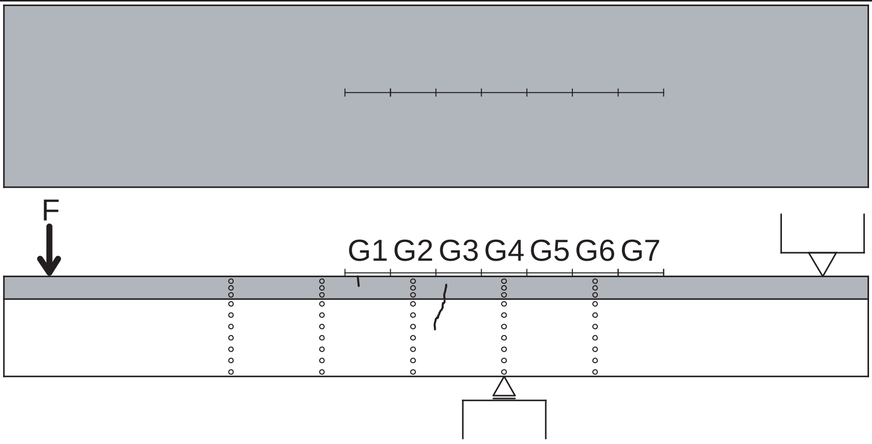
292 cycles



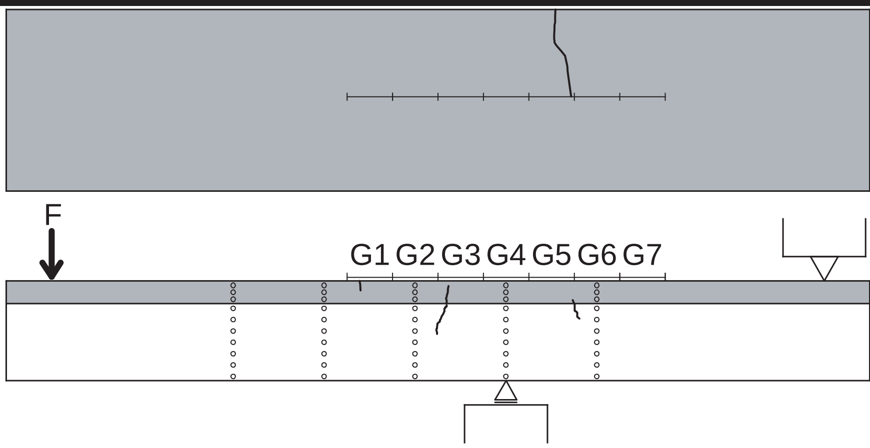
1,505 cycles



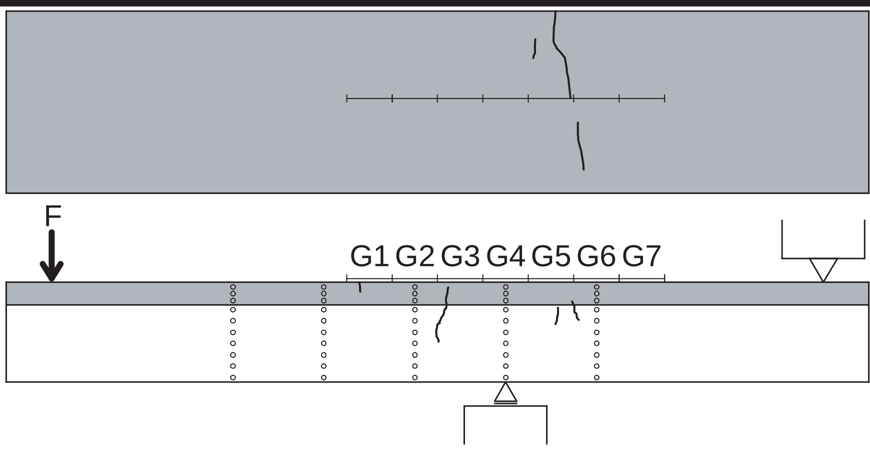
10,562 cycles



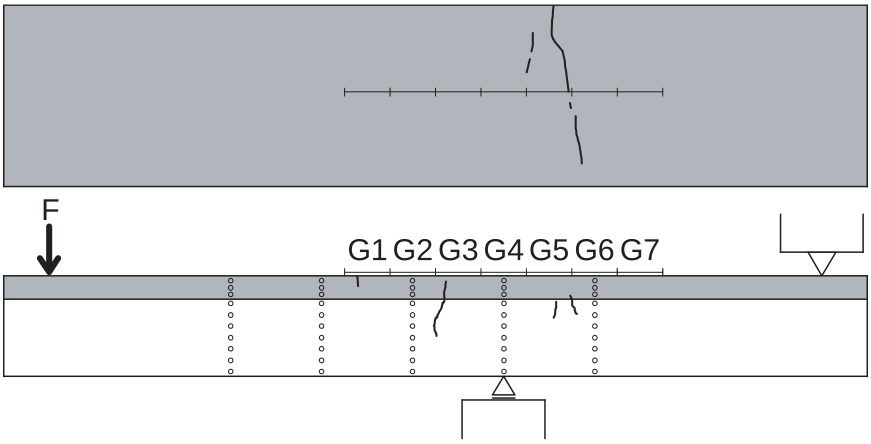
100,601 cycles



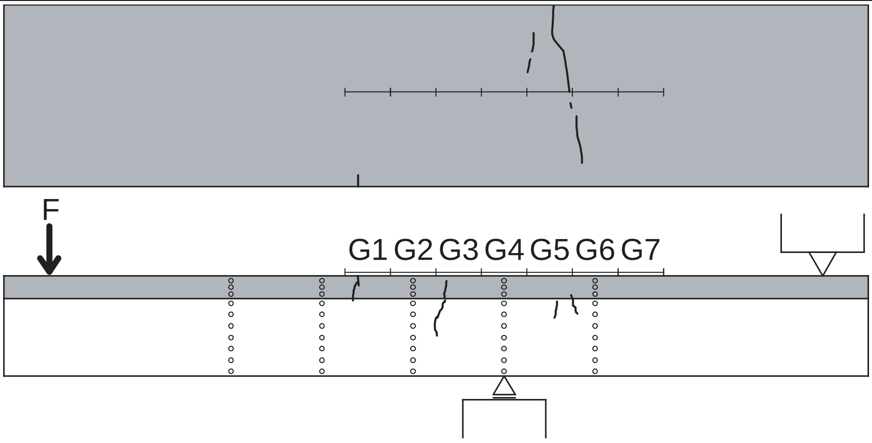
514,523 cycles



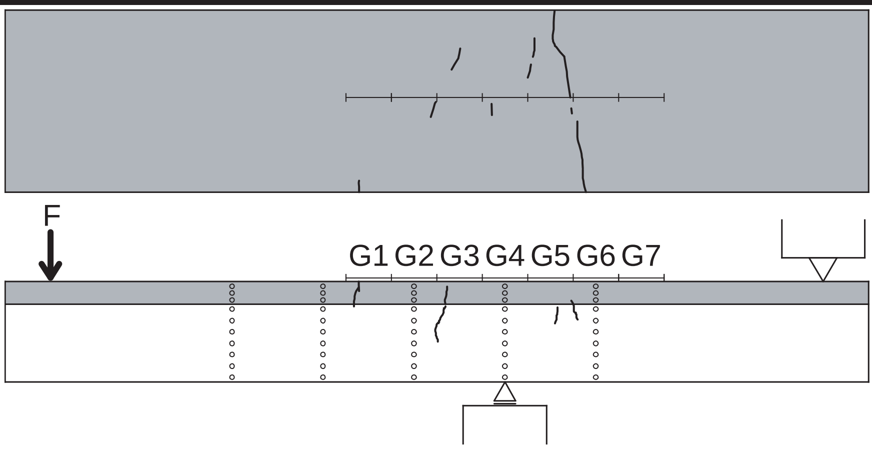
1,015,392 cycles



4,988,412 cycles



10,133,194 cycles



Second fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
45.00	4.50	0.50	1,036,448	G3 zone

Behaviour of NBF1 test specimen during the second fatigue test

Number of cycles at which steel rebars in R-UHPFRC layer fractured			
First fracture	Second fracture	Third fracture	Final fracture
863,500	1,015,500	1,023,100	1,027,400

Deflection:

Maximum deflection kept approximately constant until the first fracture of the four steel rebars in the R-UHPFRC layer. After that, the remaining three steel rebars in the R-UHPFRC layer fractured one by one, and each time steel rebar fractured, deflection growth rate became larger. Maximum deflection continued to increase until the beam behaviour became unstable.

Behaviour of deflection range was similar to that of maximum deflection, while its growth rate was always smaller than growth rate of maximum deflection.

Deformation of R-UHPFRC layer:

Only maximum deformation at G3 and G5 zones grew during the test. Maximum deformation at G3 zone increased gradually until the first fracture of four steel rebars, after which growth rate of maximum deformation at G3 zone increased. Afterwards, each time the remaining three steel rebars fractured, growth rate of maximum deformation at G3 zone became larger than before. Deformation localisation of R-UHPFRC occurred at G3 zone.

Maximum deformation at G5 zone increased slightly until the final steel rebars of the R-UHPFRC layer fractured. Maximum deformation at G1 and G4 zones kept approximately constant until the first fracture of the four steel rebars, followed by decrease of those readings with different decrease rate. Maximum deformation at G2 zone decreased from the beginning of the test until about 600,000 cycles and then became approximately constant. When the first fracture of the four steel rebars occurred, it started to decrease. Maximum deformation at G6 and G7 zones kept approximately constant until the final steel rebars of the R-UHPFRC layer fractured. When the final steel rebars of the R-UHPFRC fractured, R-UHPFRC layer at all local zones except G3 zones softened.

Behaviour of deformation range was more or less similar to that of maximum deformation.

Deformation over the entire depth of the specimen:

Until about 501,619 cycles, tensile deformation solely increased slightly. At 1,001,891 cycles just before failure of the beam, deformation over the entire depth of the specimen grew significantly, while compression fibre was unchanged.

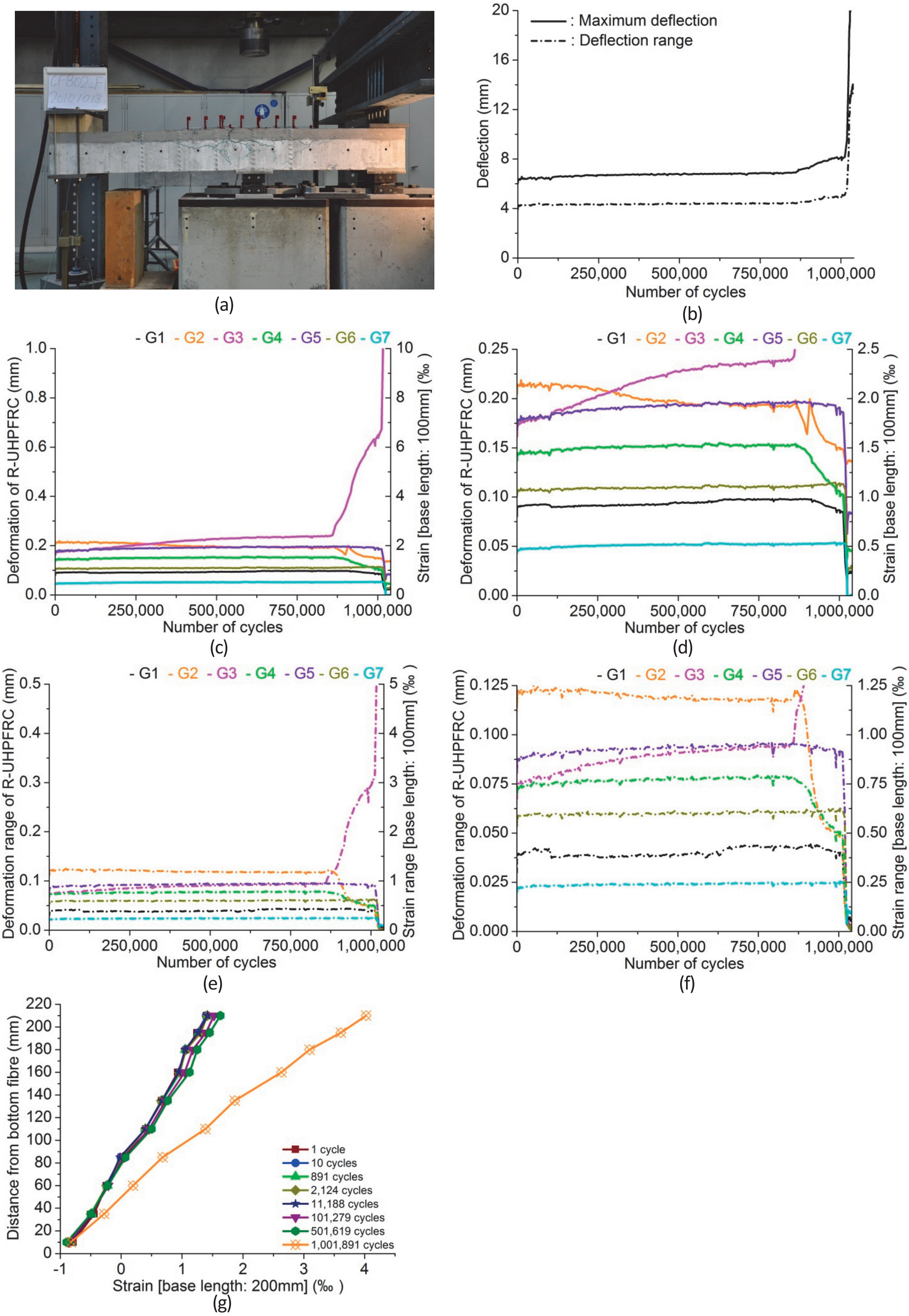


Figure 10 NBF1-ii test: (a) fractured NBF1 test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer and (d) its magnified view, (e) deformation range of R-UHPFRC layer and (f) its magnified view and (g) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF1 test specimen during the second fatigue test

<u>1 cycle:</u>

[Top surface of R-UHPFRC layer]

- A crack almost perpendicular to the longitudinal axis of the beam developed at G2 zone.

<u>501,619 cycles:</u>

[Top surface of R-UHPFRC layer]

- Two cracks perpendicular to the longitudinal axis of the beam developed at G3 zone. One appeared close to transversal centre and another at the edge of the R-UHPFRC layer.

<u>1,001,891 cycles:</u>

[Top surface of R-UHPFRC layer]

- Three existing cracks at G3 zone coalesced and a long crack approximately perpendicular to the longitudinal axis of the beam appeared.
- Significant change wasn't observed on the other existing cracks from the beginning of the test untill 1,001,891 cycles.

[Side of RU-RC beam]

- From an existing crack at G3 zone, two horizontal cracks developed. One crack grew from the lower tip of the existing crack to cantilever end. Another grew from the position of top steel rebars of the RC part towards fixed support.
- Significant change wasn't observed on the other existing cracks from the beginning of the test till 1,001,891 cycles.

<u>Failure (1,036,448 cycles):</u>

[Top surface of R-UHPFRC layer]

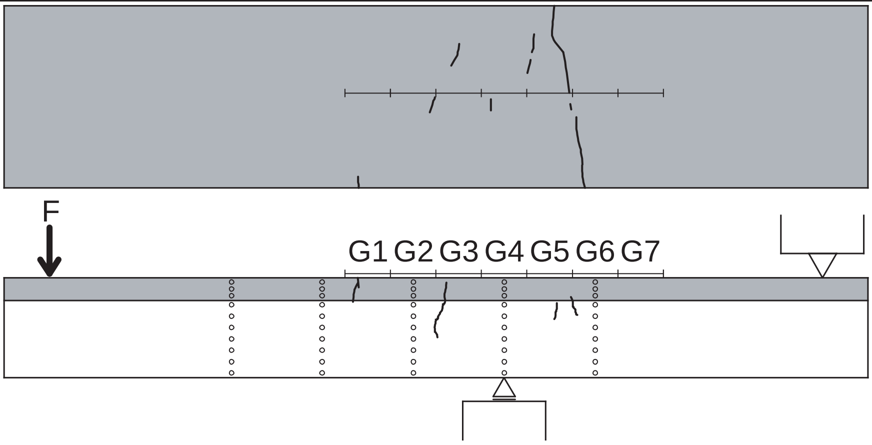
- A fracture crack perpendicular to the longitudinal axis of the beam appeared at G3 zone. Most part of the fracture crack was formed by increasing the width of existing cracks. No change was observed on the other existing cracks.

[Side of RU-RC beam]

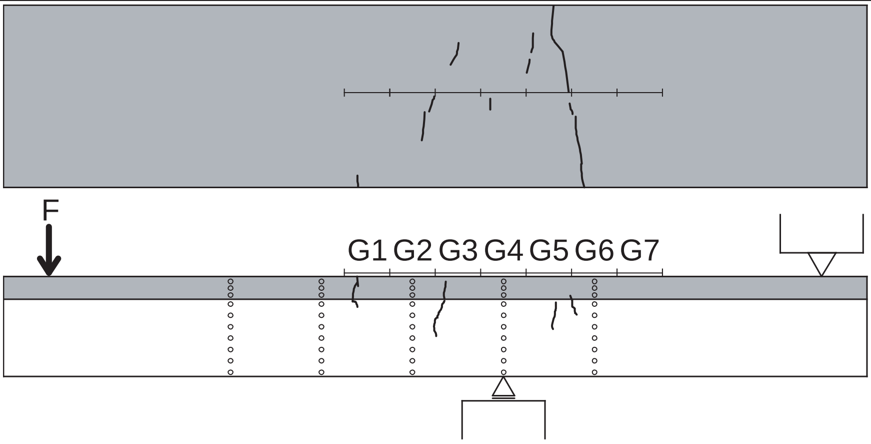
- Vertical and horizontal fracture cracks developed in the R-UHPFRC layer and RC part respectively by increasing the length and width of existing cracks. The horizontal fracture crack ran approximately on the position of top steel rebars of the RC part towards fixed support.
- Inclined flexure-shear cracks developed from movable support to both cantilever end and fixed support. At the position of top steel rebars of the RC part, these flexure-shear cracks changed to horizontal cracks.

Evolution of crack pattern on NBF1 test specimen during the second fatigue test

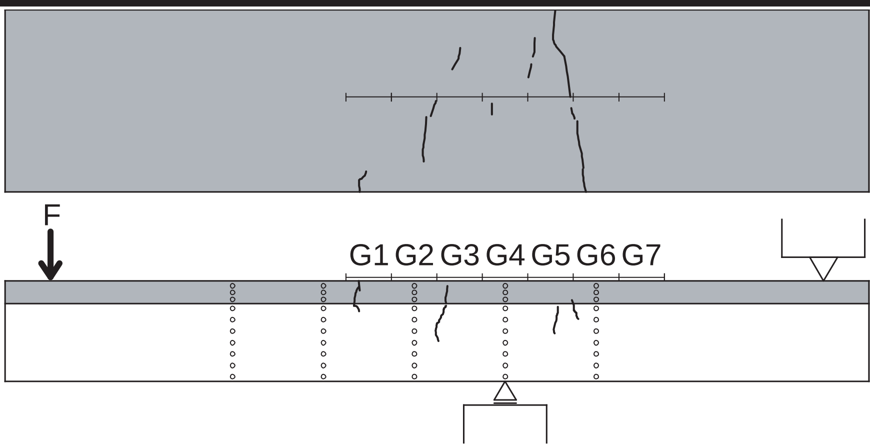
0 cycle



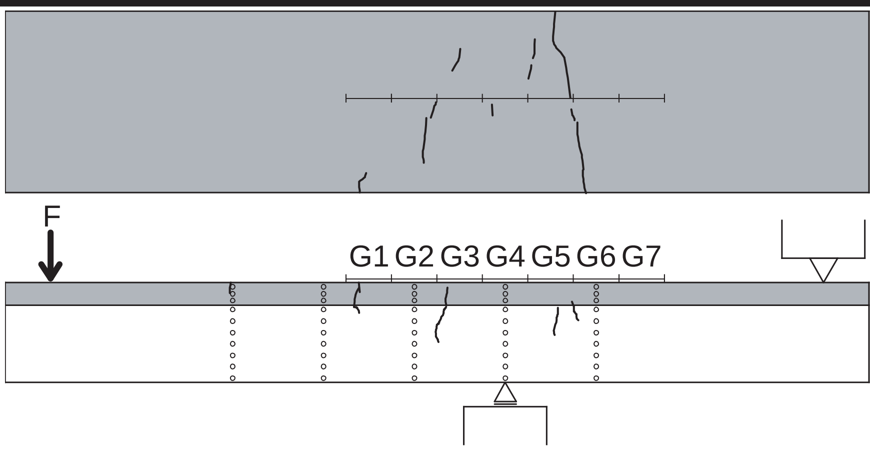
1 cycle



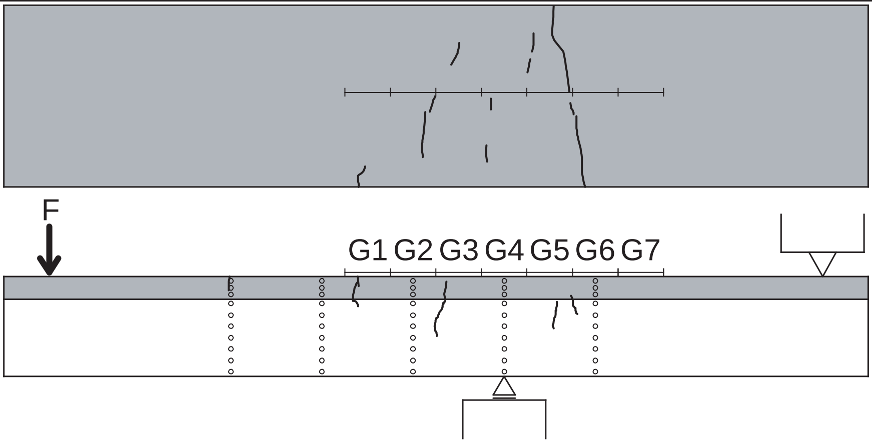
10 cycles



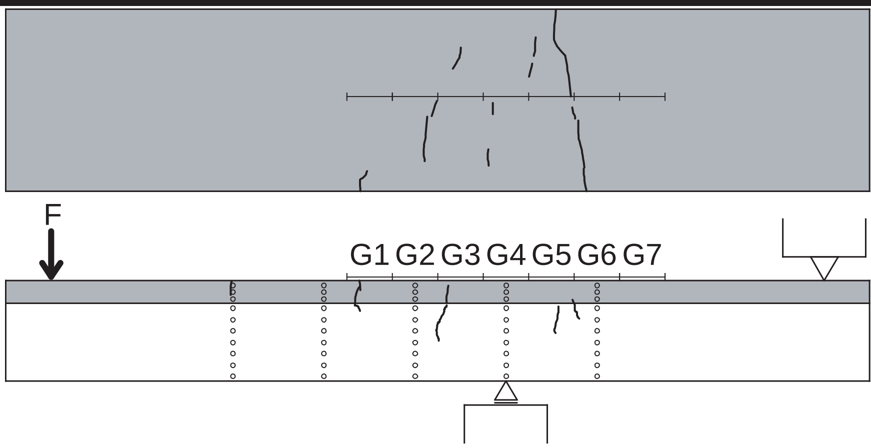
891 cycles



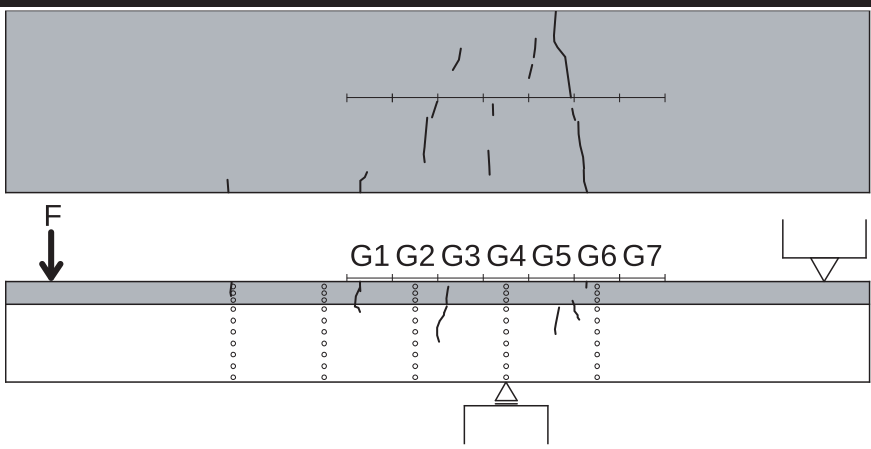
2,124 cycles



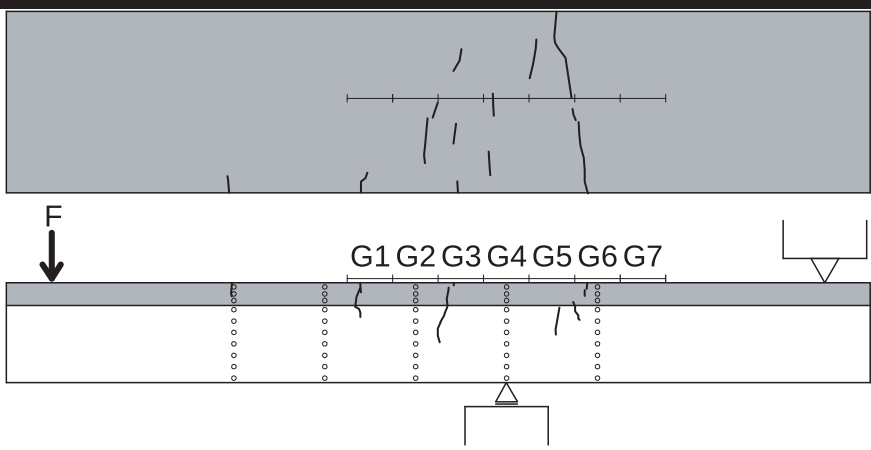
11,188 cycles



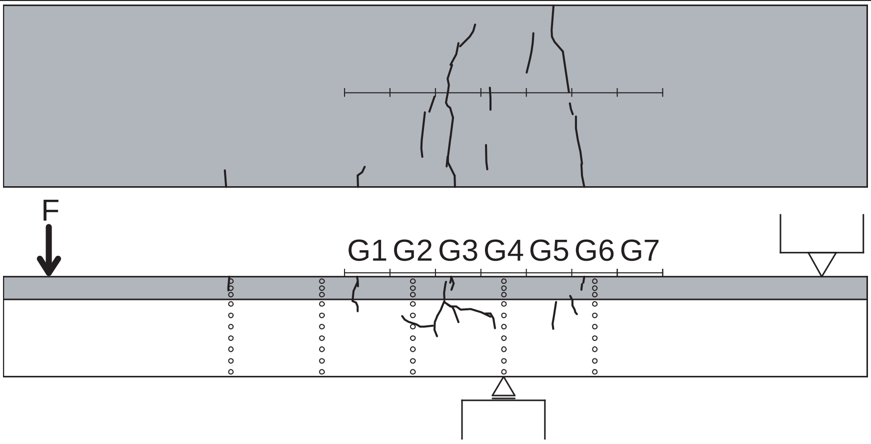
101,279 cycles



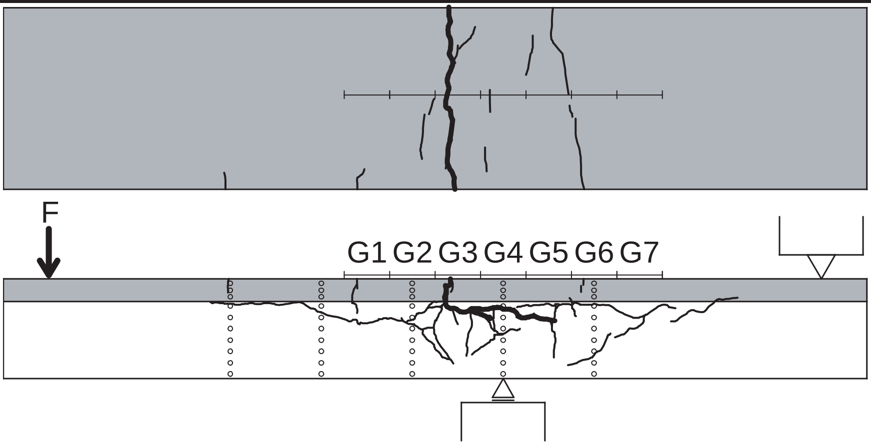
501,619 cycles



1,001,891 cycles



Failure (1,036,448 cycles)



5.2 NBF2 test

First fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
40.50	4.05	0.40	20,004,397	run-out

Behaviour of NBF2 test specimen during the first fatigue test

Deflection:

Maximum deflection rapidly increased during the first 500,000 cycles and then kept more or less constant until the end of the test.

Deflection range rapidly increased during the first 200,000 cycles. After that, it kept approximately constant until the end of the test.

Deformation of R-UHPFRC layer:

Maximum deformation at all local zones rapidly grew until about 500,000 cycles and then kept approximately constant until the end of the test. Distribution of maximum deformation didn't correspond to distribution of acting moment and variations were observed on deformation readings.

Deformation range at all local zones rapidly increased during the first 200,000 cycles, followed by almost constant deformation range until the end of the test.

Deformation over the entire depth of the specimen:

Until about 1,002,764 cycles, 90 % of deformation was attained with respect to the deformation at the end of the test. Tensile deformation grew more substantially than compressive deformation.

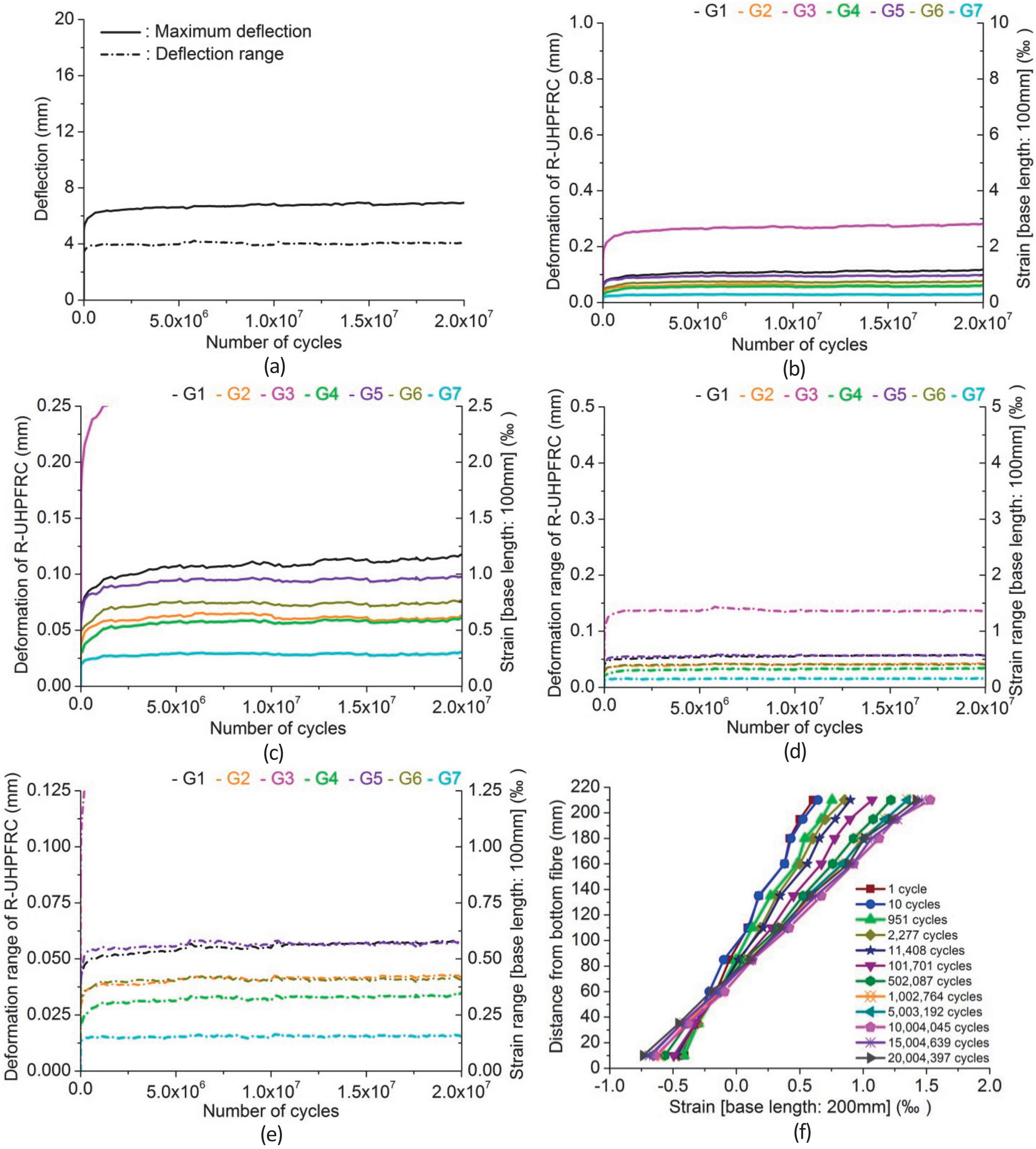


Figure 11 NBF2-i test: growth curves of (a) maximum deflection and deflection range, (b) maximum deformation of R-UHPFRC layer and (c) its magnified view, (d) deformation range of R-UHPFRC layer and (e) its magnified view and (f) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF2 test specimen during the first fatigue test

<u>0 cycle:</u>

[Side of RU-RC beam]

- A horizontal crack was initially observed on the R-UHPFRC – RC interface, extending from G5 to G7 zone.

<u>1 cycle:</u>

[Top surface of R-UHPFRC layer]

- A short crack appeared on the G3 – G4 zone border at edge of the beam.

[Side of RU-RC beam]

- Short vertical cracks were caused at G3 to G5 zones in the R-UHPFRC layer.

<u>2,277 cycles:</u>

[Top surface of R-UHPFRC layer]

- A crack with an angle of 20˚ from the transversal axis developed on the border between G3 and G4 zone.

[Side of RU-RC beam]

- An existing vertical crack at G5 zone in the R-UHPFRC layer propagated into the RC part.

<u>11,408 cycles:</u>

[Top surface of R-UHPFRC layer]

- A short crack perpendicular to the longitudinal axis of the beam appeared at G3 zone.

[Side of RU-RC beam]

- A crack inclined from the vertical axis with an angle of 20˚ toward cantilever end was caused at outside of G1 zone in the R-UHPFRC layer.

<u>502,087 cycles:</u>

[Top surface of R-UHPFRC layer]

- A crack was caused close to existing cracks at the transversal centre of G3 zone.

[Side of RU-RC beam]

- A few vertical cracks developed in the R-UHPFRC layer.
- An existing crack at outside of G1 zone in the R-UHPFRC layer propagated into the RC part.
- An existing short vertical crack at G3 zone in the R-UHPFRC layer increased its length.

<u>1,002,764 cycles:</u>

[Side of RU-RC beam]

- An existing crack at G3 zone in the R-UHPFRC layer propagated into the RC part.

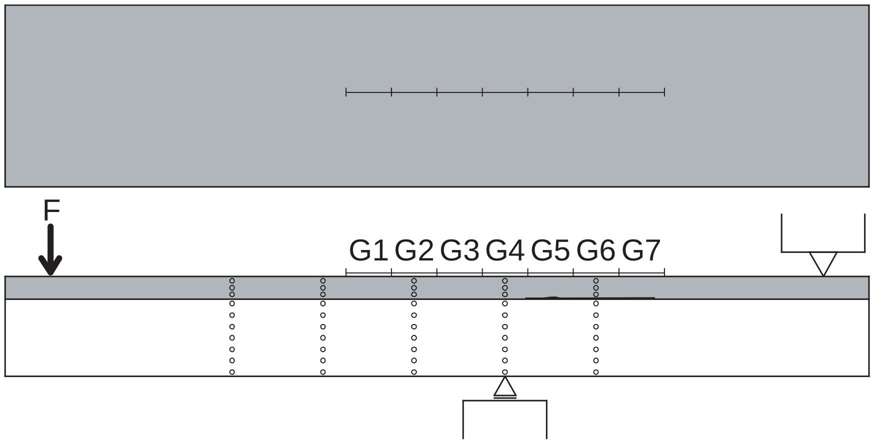
<u>5,003,192 cycles:</u>

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

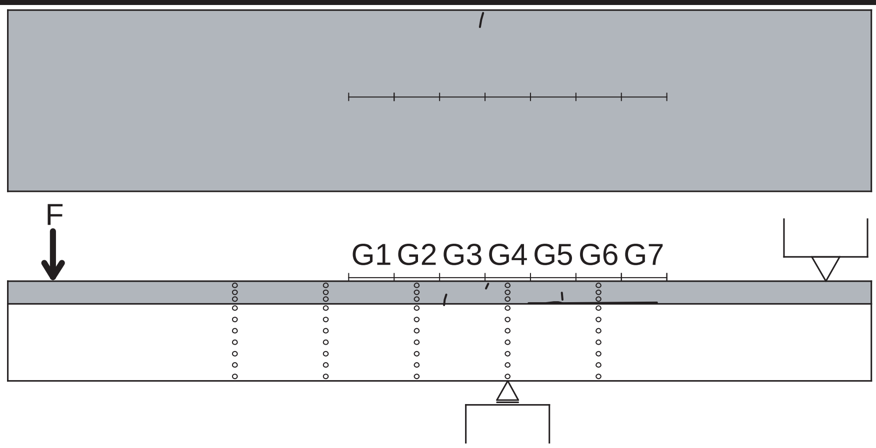
- Formation of new cracks and propagation of existing cracks started to concentrate at G3 zone.

Evolution of crack pattern on NBF2 test specimen during the first fatigue test

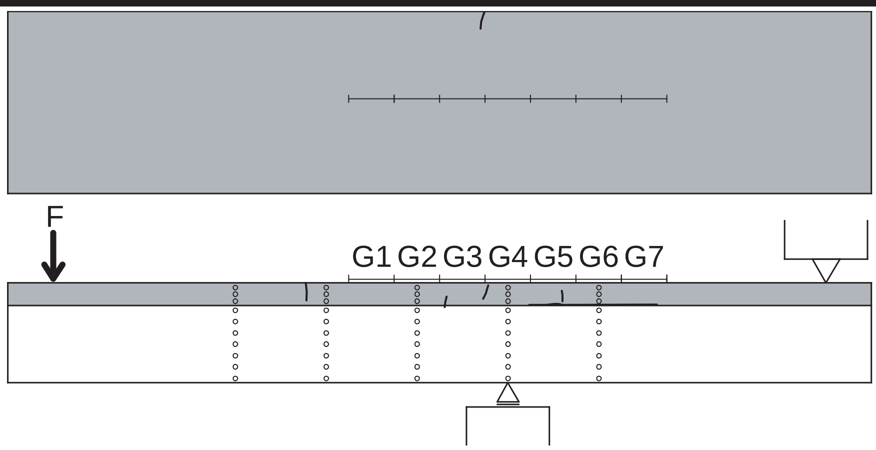
0 cycle



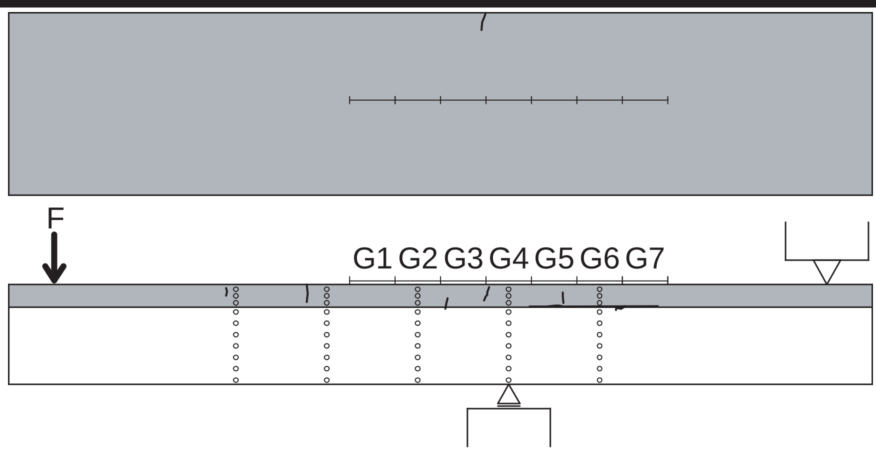
1 cycle



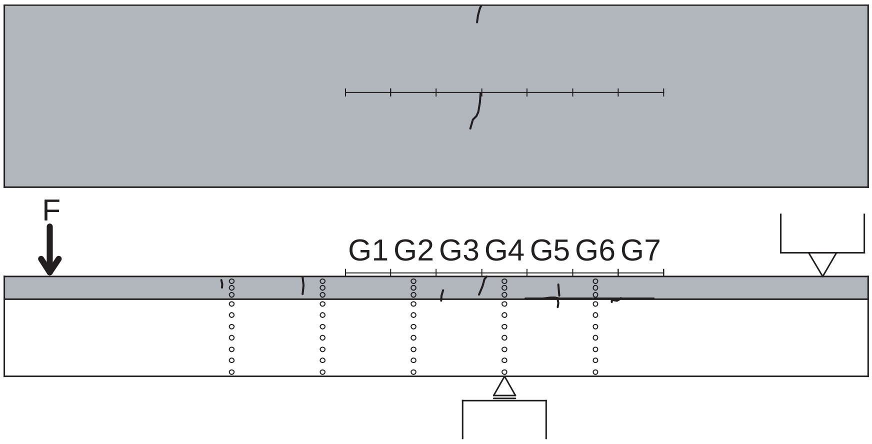
10 cycles



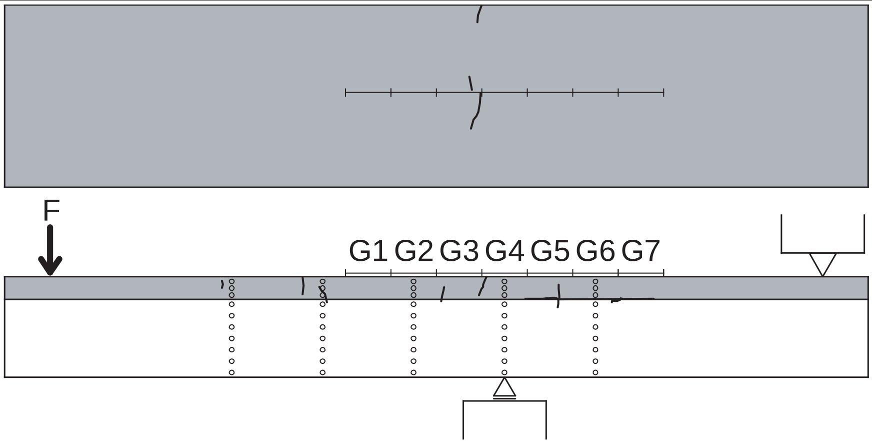
951 cycles



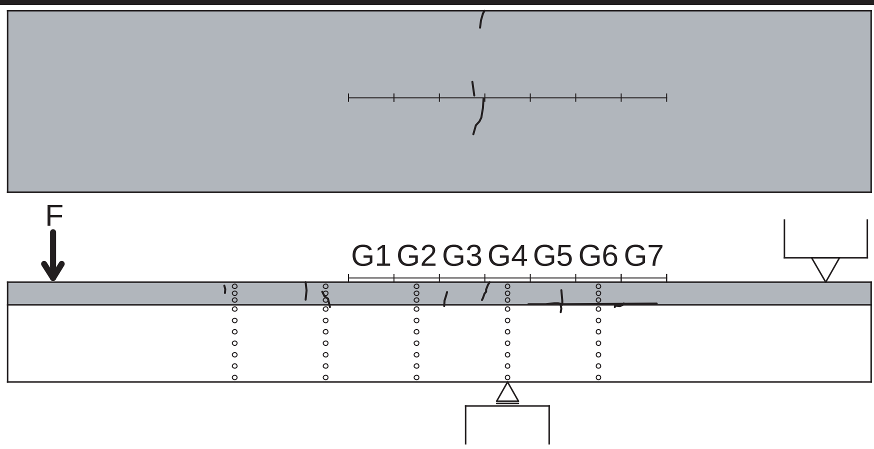
2,277 cycles



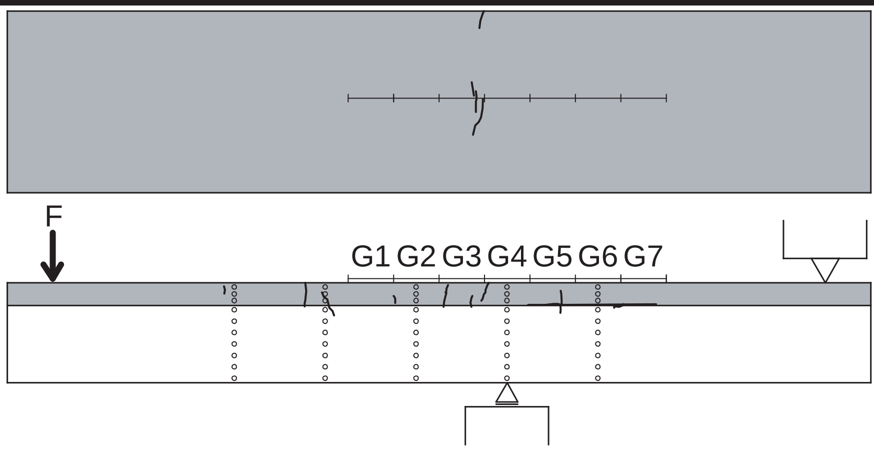
11,408 cycles



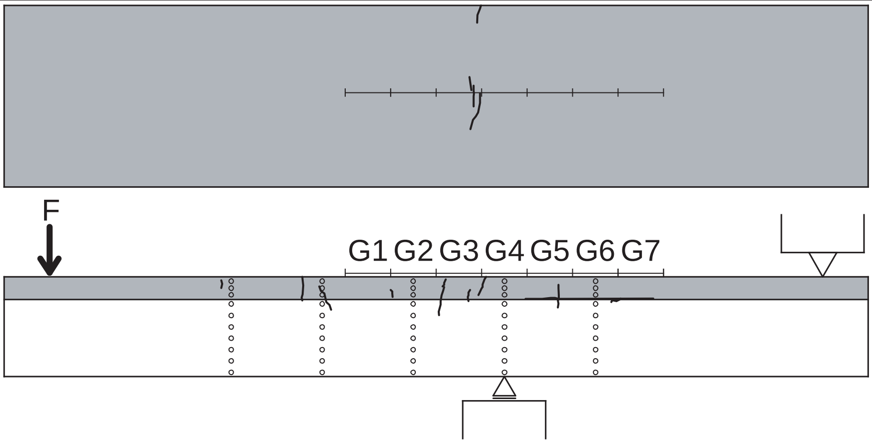
101,701 cycles



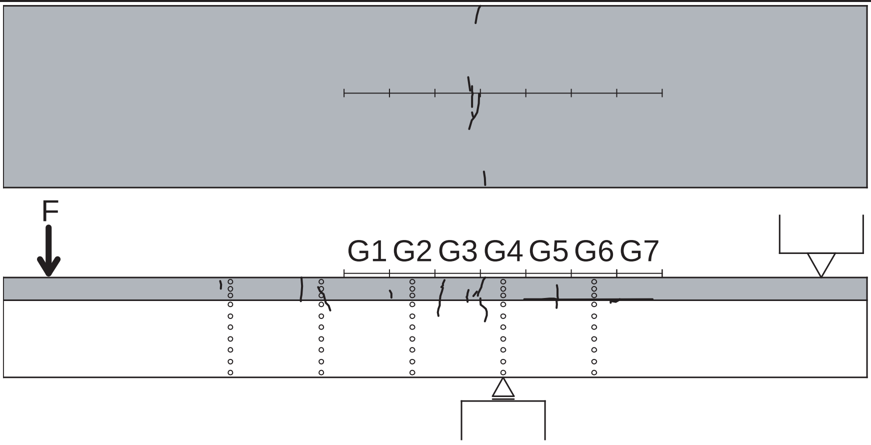
502,087 cycles



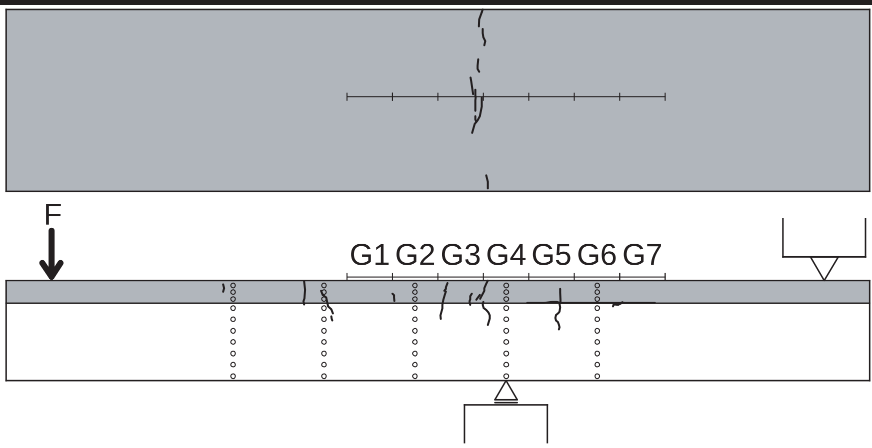
1,002,764 cycles



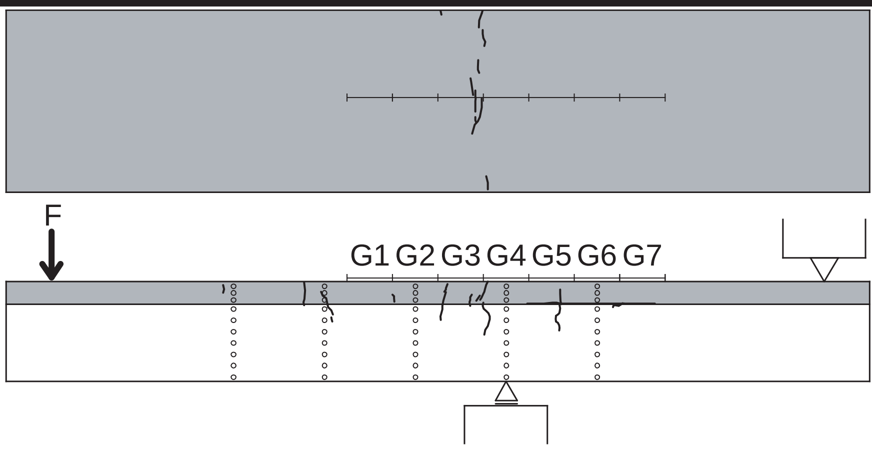
5,003,192 cycles



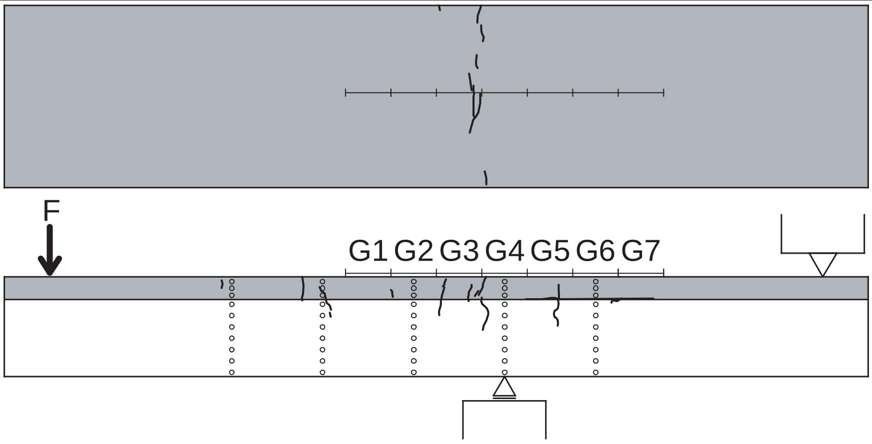
10,004,045 cycles



15,004,639 cycles



20,004,397 cycles



Second fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
45.00 kN	4.50 kN	0.50	1,966,944	G3 zone

Behaviour of NBF2 test specimen during the second fatigue test

Number of cycles at which steel rebars in R-UHPFRC layer fractured			
First fracture	Second fracture	Third fracture	Final fracture
1,762,700	1,930,300	1,951,300	1,955,450

Deflection:

Maximum deflection kept roughly constant until the first fracture of the four steel rebars in the R-UHPFRC layer, after which it started to increase. Subsequently, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, maximum deflection growth rate became larger than before. Maximum deflection continued to increase until the beam behaviour became unstable.

Behaviour of deflection range was similar to that of maximum deflection, while its growth rate was always smaller than growth rate of maximum deflection.

Deformation of R-UHPFRC layer:

Maximum deformation at G3 zone was excessively larger than the other local zones. It increased slightly until about 825,900 cycles at which its reading suddenly rose by about 0.02 mm and then its growth rate slightly increased. When one of the four steel rebars in R-UHPFRC layer fractured, growth rate of maximum deformation at G3 zone significantly increased. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deformation at G3 zone became larger than before. Deformation localisation of the R-UHPFRC occurred at G3 zone.

Maximum deformation at G1, G6 and G7 zones grew slightly until the second fracture of the four steel rebars in the R-UHPFRC layer occurred, at which R-UHPFRC at G1, G6 and G7 zones softened.

Maximum deformation at G2, G4 and G5 zones kept approximately constant until the first fracture of the four steel rebars in the R-UHPFRC layer occurred, after which it started to decrease. When one of the remaining three steel rebars in the R-UHPFRC layer fractured, R-UHPFRC at G2, G4 and G5 zones softened.

At all zones, behaviour of deformation range was approximately similar to that of maximum deformation.

Deformation over the entire depth of the specimen:

Increase of deformation over the beam depth was quite small until 1,001,014 cycles.

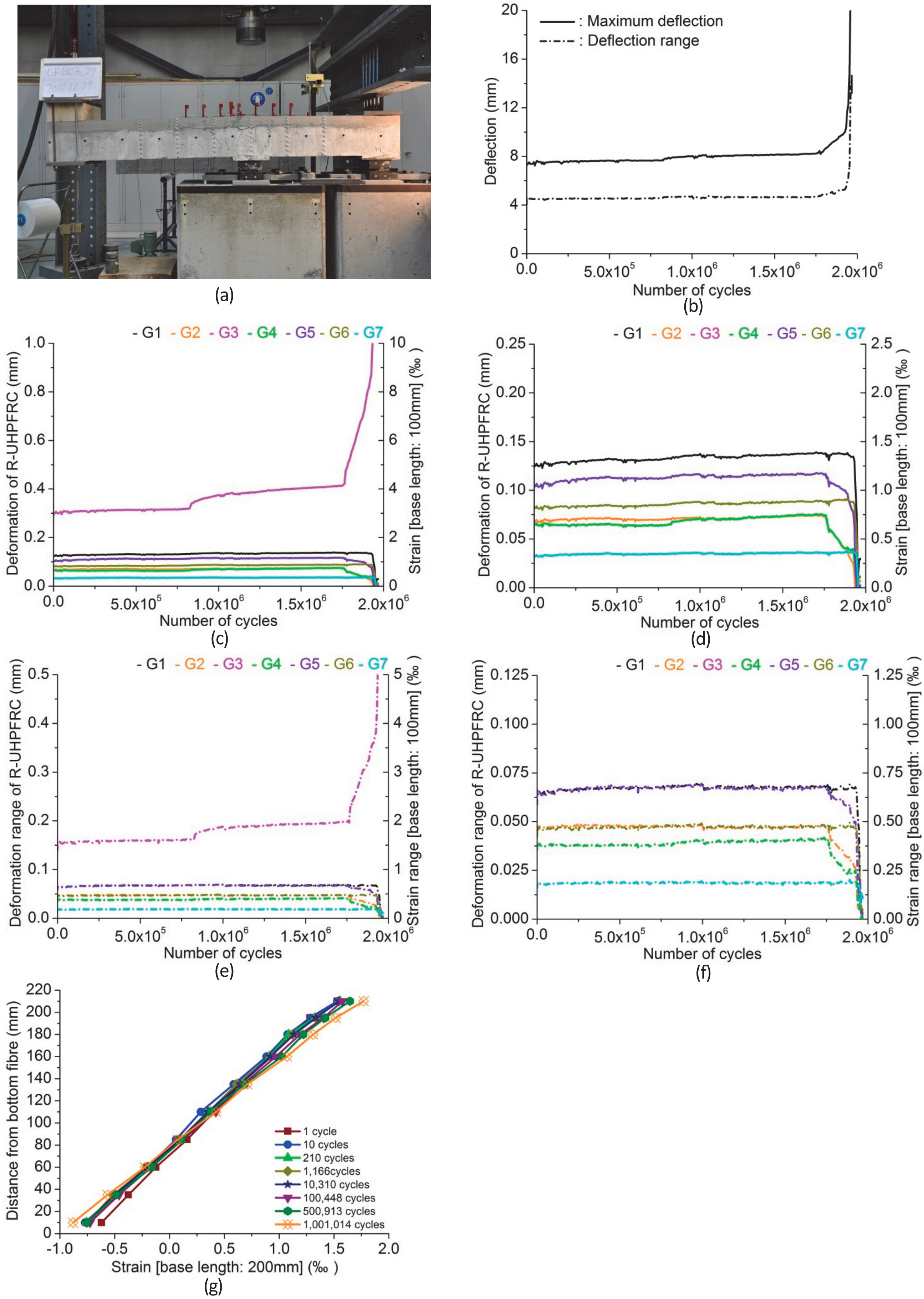


Figure 12 NBF2-ii test: (a) fractured NBF2 test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer and (d) its magnified view, (e) deformation range of R-UHPFRC layer and (f) its magnified view and (g) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF2 test specimen during the second fatigue test

0 to 1,001,014 cycles:

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

- Significant change wasn't observed on existing cracks.

Failure (1,966,944 cycles):

[Top surface of R-UHPFRC layer]

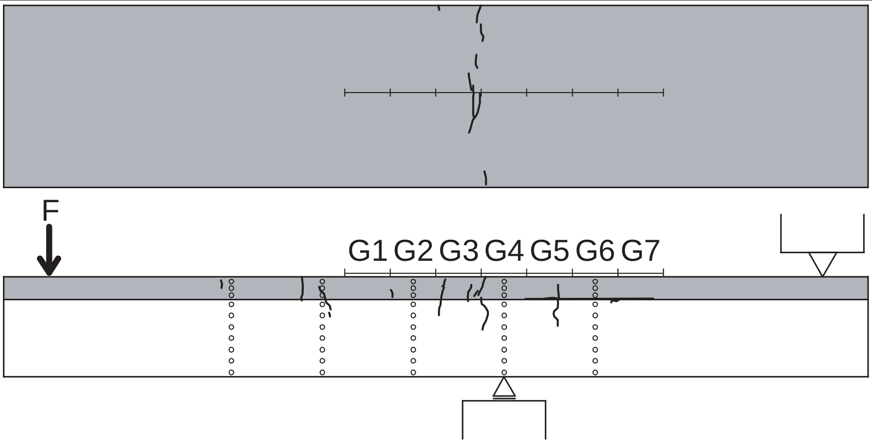
- A fracture crack approximately perpendicular to the longitudinal axis of the beam appeared at G3 zone. Existing cracks coalesced to form the fracture crack.

[Side of RU-RC beam]

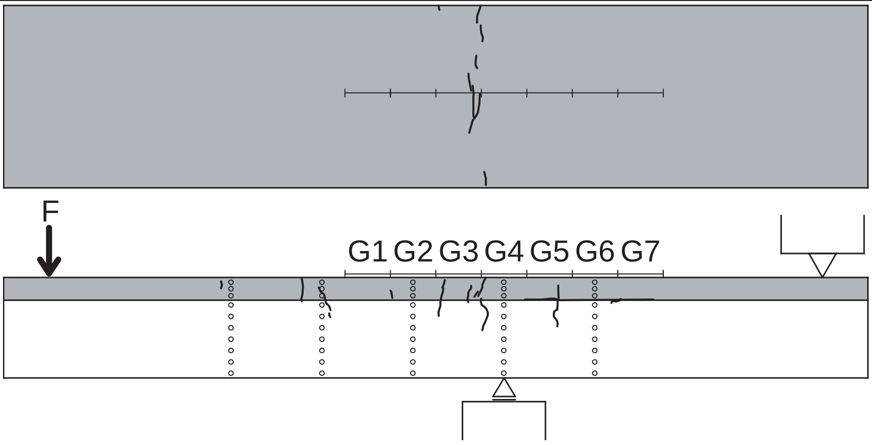
- A fracture crack developed in the R-UHPFRC layer with an angle of 30 ° to horizontal axis.
- A horizontal fracture crack developed in the RC part and ran approximately on the position of top steel rebars of the RC part. It propagated from outside of G1 zone to G7 zone and coalesced with initially existing horizontal crack on the R-UHPFRC – RC interface between G5 and G7 zone.
- Existing vertical cracks at G3 and G5 zones in the RC part increased those lengths.
- An inclined flexure-shear crack developed from an existing crack at G2 zone to movable support.

Evolution of crack pattern on NBF2 test specimen during the second fatigue test

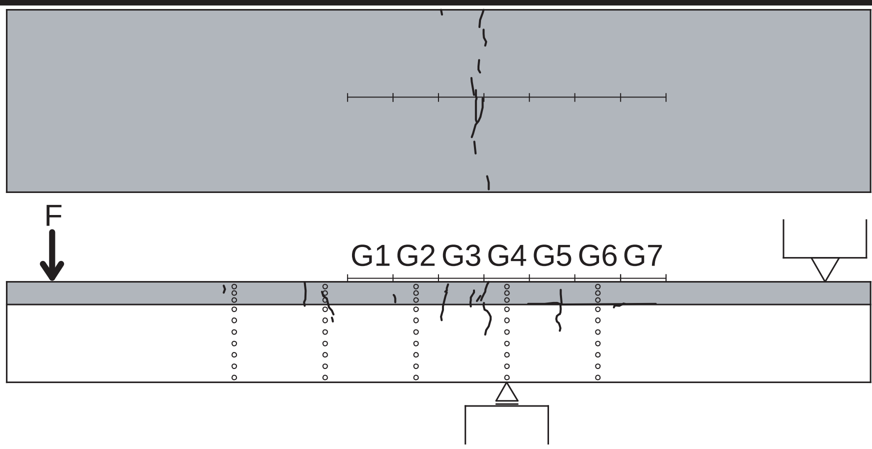
0 cycle



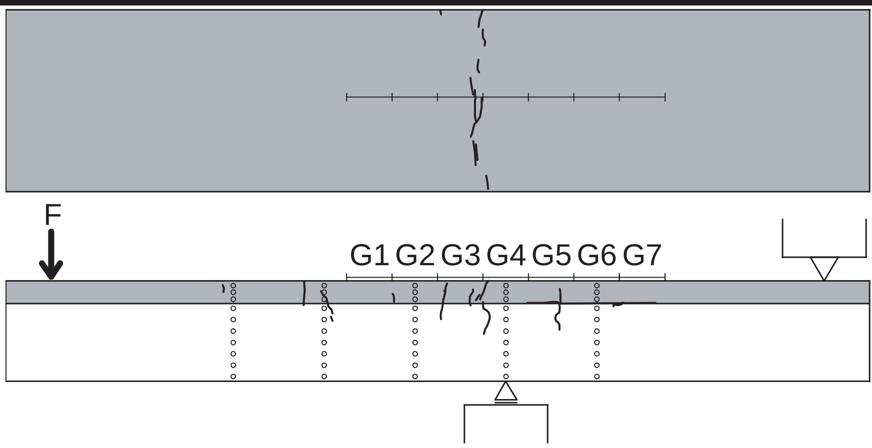
1 cycle



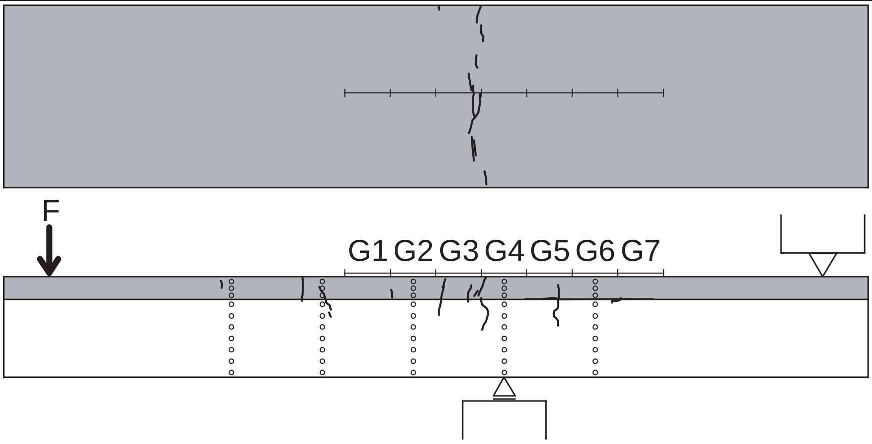
10 cycles



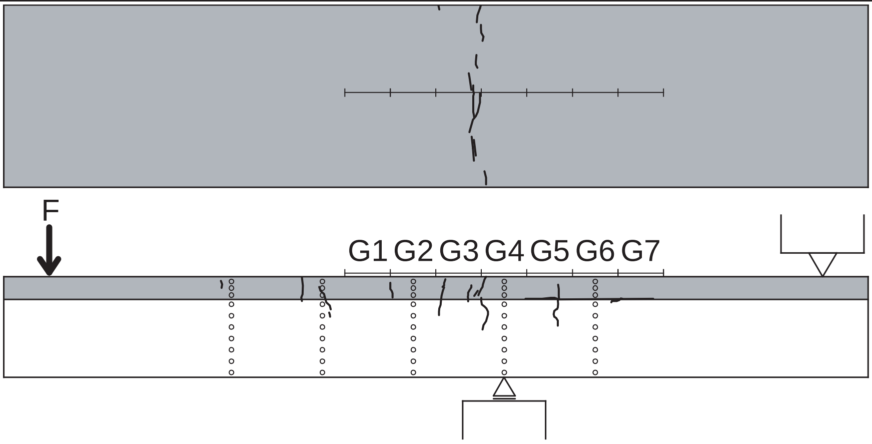
210 cycles



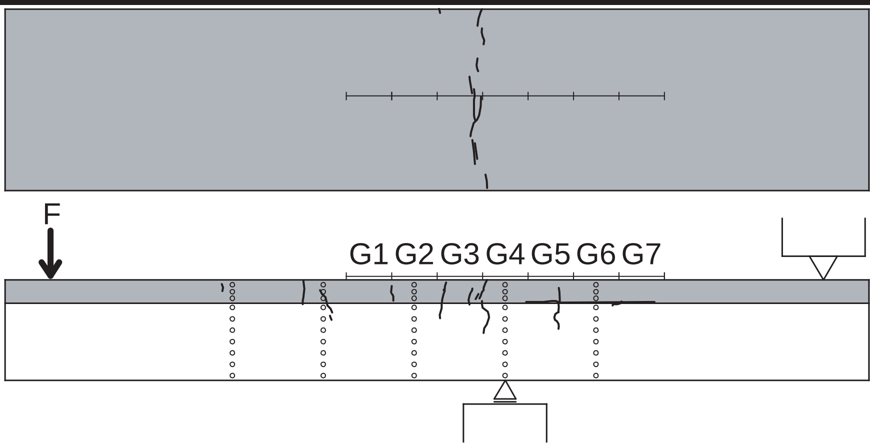
1,166 cycles



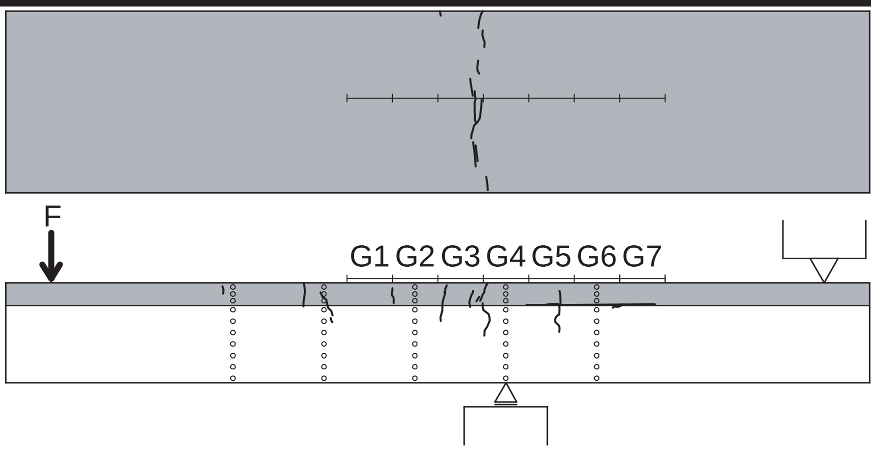
10,310 cycles



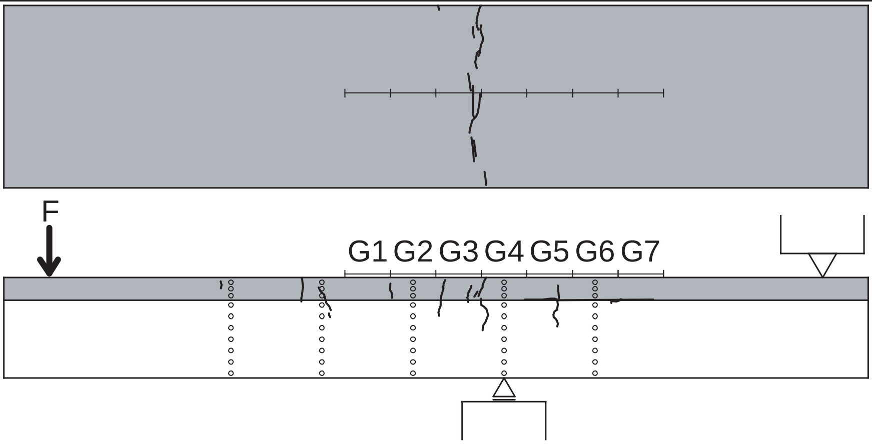
100,448 cycles



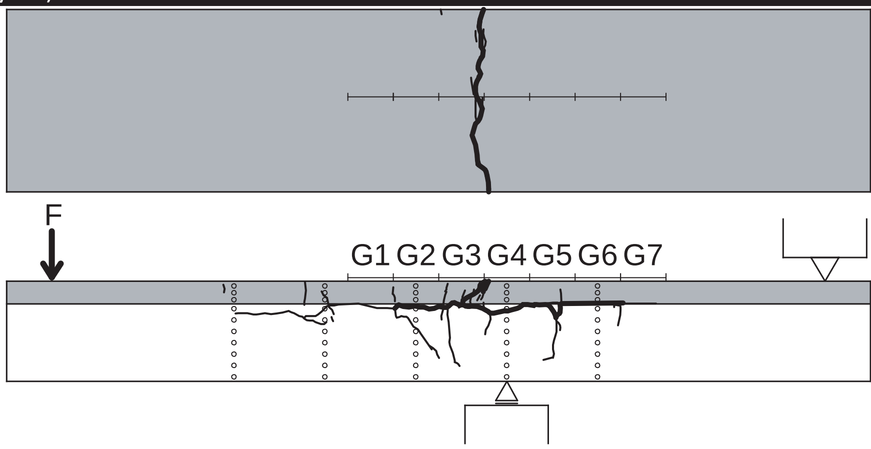
500,913 cycles



1,001,014 cycles



Failure (1,966,944 cycles)



5.3 NBF3 test

<u>**First fatigue test**</u>

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
45.00 kN	4.50 kN	0.50	23,935,641	run-out

Behaviour of NBF3 test specimen during the first fatigue test

<u>Deflection:</u>

Maximum deflection rapidly grew until about 50,000 cycles, after which it grew slightly until the end of the test.

Deflection range rapidly grew during the first 1,000 cycles, and then kept approximately constant until the end of the test.

<u>Deformation of R-UHPFRC layer:</u>

Maximum local deformation at G1 to G5 zones rapidly grew until about 200,000 cycles, and then its growth rate became significantly lower than before. Maximum local deformation at G6 and G7 zone rapidly grew during the first 50,000 cycles, and then kept growing to the end of the test with smaller growth rate than before. Growth rate of maximum deformation was similar among all local zones. Distribution of maximum deformation didn't correspond to distribution of acting moment and variation was observed on deformation readings.

Behaviour of deformation range of all local zones was almost the same as that of maximum local deformation.

<u>Deformation over the entire depth of the specimen:</u>

Until about 510,486 cycles, 90 % of deformation over the beam depth was attained with respect to the deformation at the end of the test. Tensile deformation grew more substantially than compressive deformation, and thus the position of neutral axis of the beam gradually reached compressive fibre.

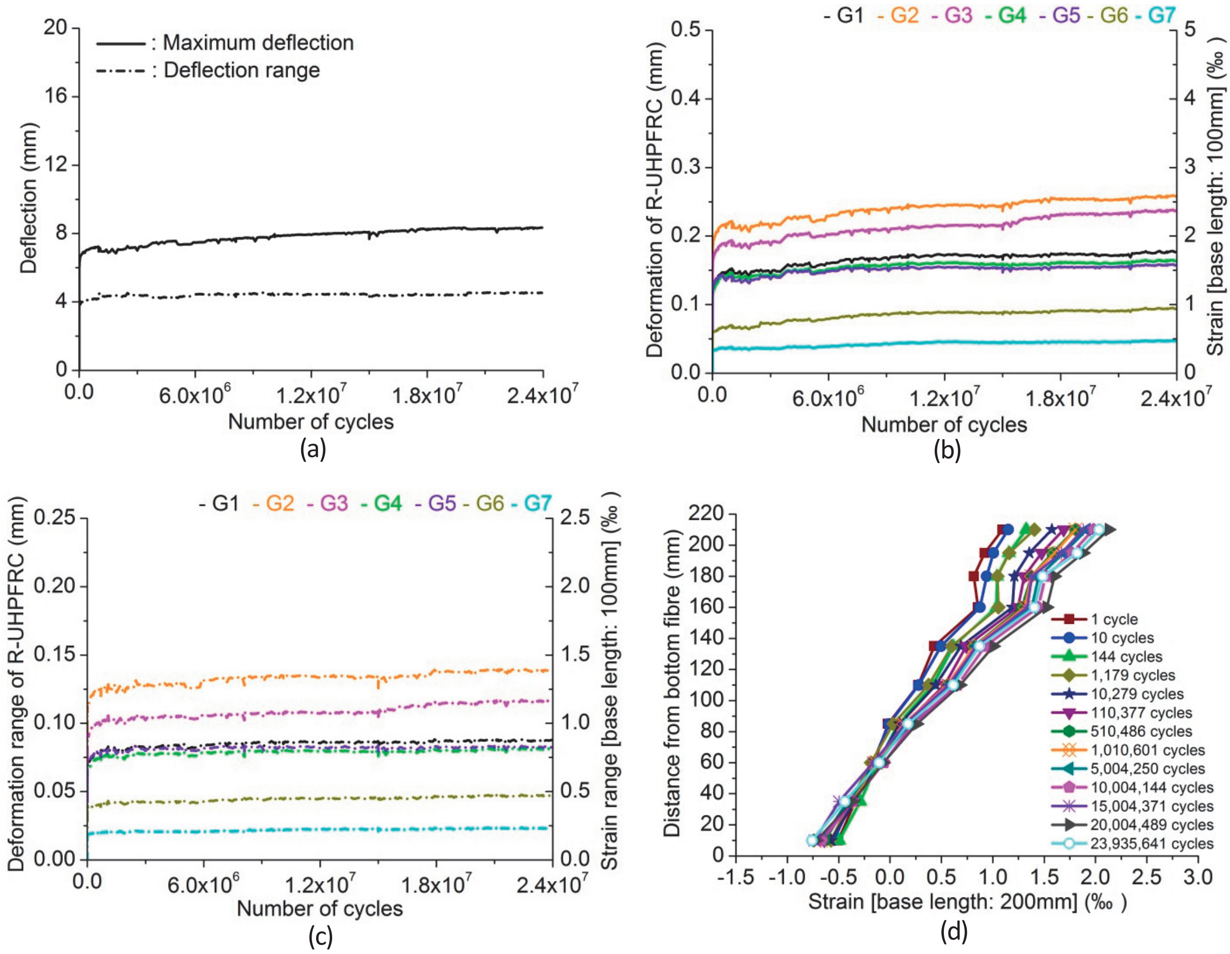


Figure 13 NBF3-i test: growth curves of (a) maximum deflection and deflection range, (b) maximum deformation of R-UHPFRC layer and (c) its magnified view, (d) deformation range of R-UHPFRC layer and (e) its magnified view and (f) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF3 test specimen during the first fatigue test

<u>1 cycle:</u>

[Top surface of R-UHPFRC layer]

- At both edges of the beam two very short cracks perpendicular to the longitudinal axis of the beam appeared: one was on the G2 – G3 zone border, and another at G4 zone.

[Side of RU-RC beam]

- A crack slightly inclined from vertical axis was caused at G2 zone crossing the R-UHPFRC – RC interface.

<u>144 cycles:</u>

[Side of RU-RC beam]

- A new crack slightly inclined from vertical axis was caused at G5 zone crossing the R-UHPFRC – RC interface. An existing crack at G2 zone increased its length to bottom of the beam.

<u>110,377 cycles:</u>

[Side of RU-RC beam]

- A vertical crack crossing the R-UHPFRC – RC interface developed at G1 zone.

<u>1,010,601 cycles:</u>

[Top surface of R-UHPFRC layer]

- A crack perpendicular to the longitudinal axis of the beam appeared close to the edge of the beam at G3 zone.

[Side of RU-RC beam]

- A short vertical crack developed on the G2 – G3 zone border in the R-UHPFRC layer from a crack at the edge of top surface of the R-UHPFRC layer.

<u>5,004,250 cycles:</u>

[Top surface of R-UHPFRC layer]

- A crack approximately perpendicular to the longitudinal axis of the beam appeared close to the transversal centre of the beam at G3 zone.

[Side of RU-RC beam]

- A vertical crack developed from the R-UHPFRC – RC interface to bottom of the beam at G4 zone.

<u>20,004,489 cycles:</u>

[Top surface of R-UHPFRC layer]

- A diagonal crack appeared close to the transversal centre of the beam on the G3 – G4 zone border.
- An existing crack at G3 zone propagated to the transversal centre of the beam.

<u>23,935,641 cycles:</u>

[Top surface of R-UHPFRC layer]

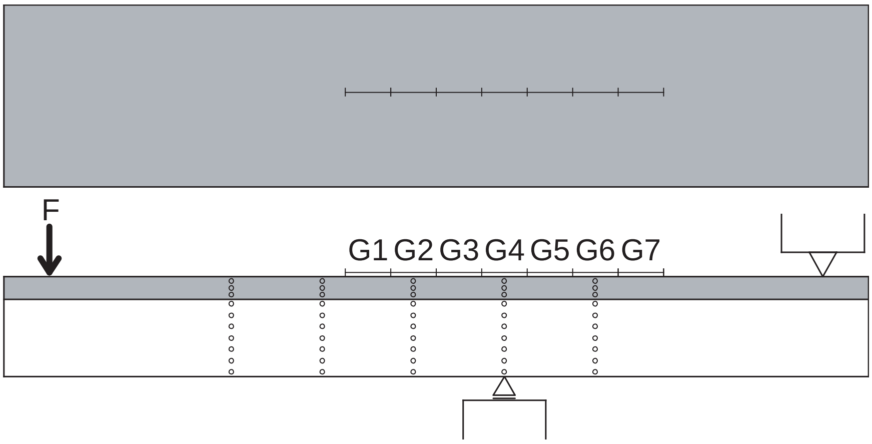
- A diagonal crack appeared at G2 zone.

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

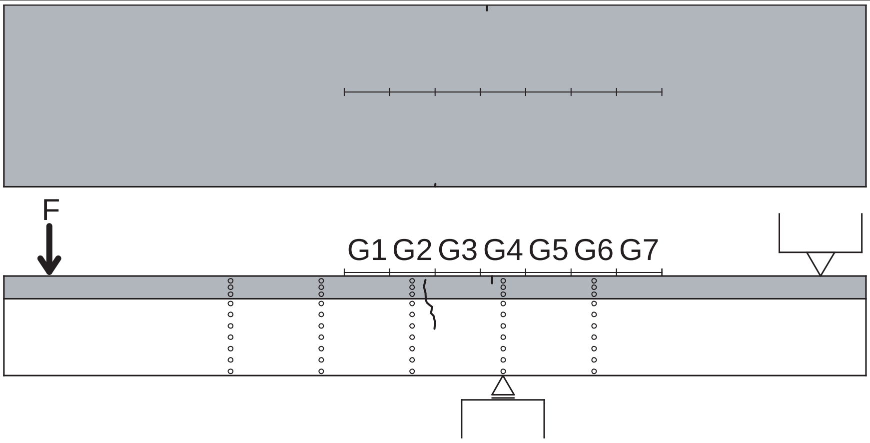
- Significant change wasn’t observed on existing cracks.

Evolution of crack pattern on NBF3 test specimen during the first fatigue test

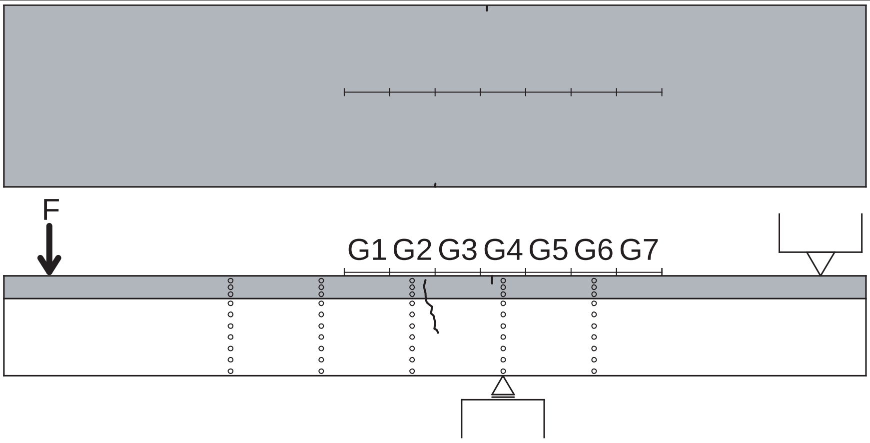
0 cycle



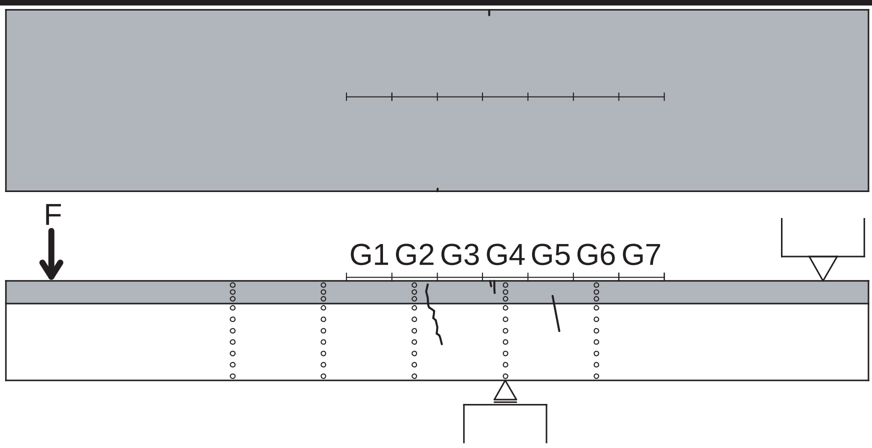
1 cycle



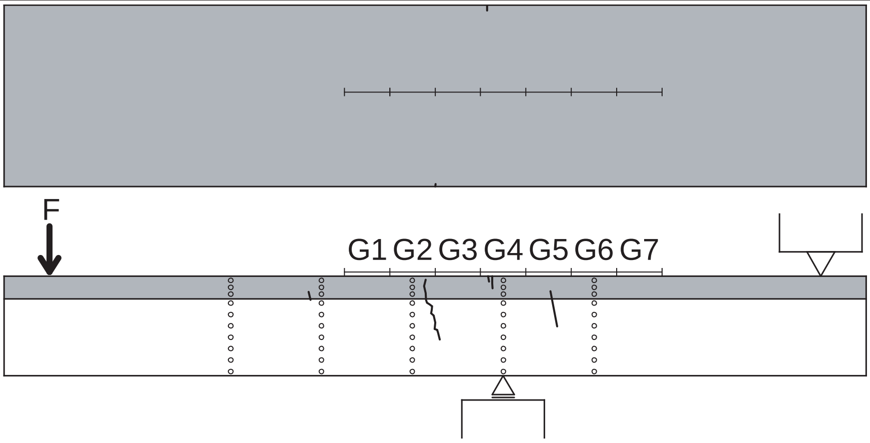
10 cycles



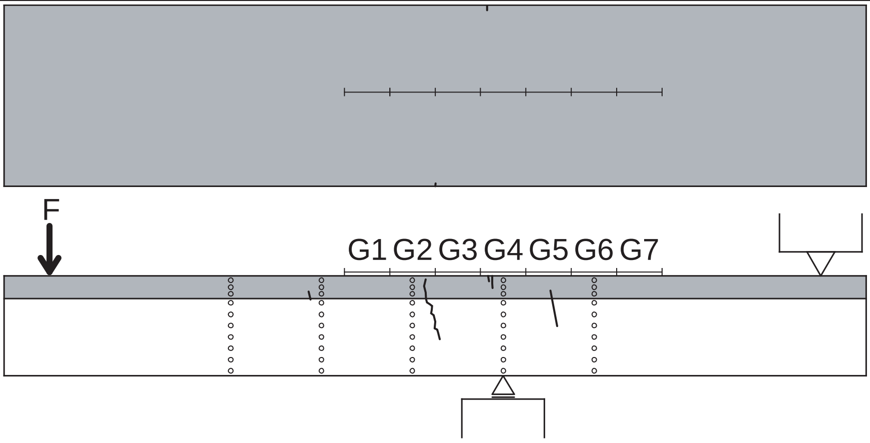
144 cycles



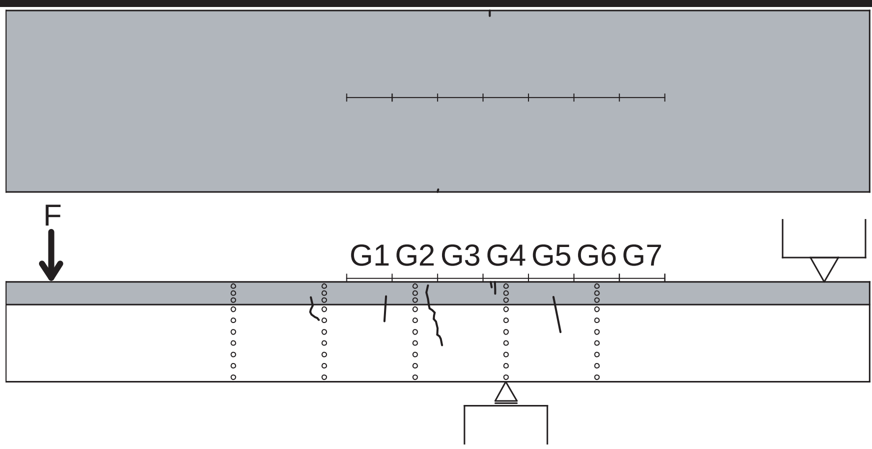
1,179 cycles



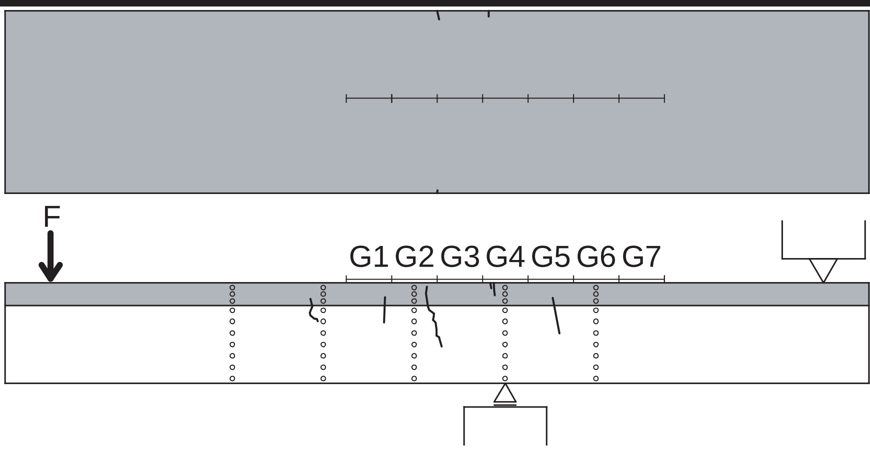
10,279 cycles



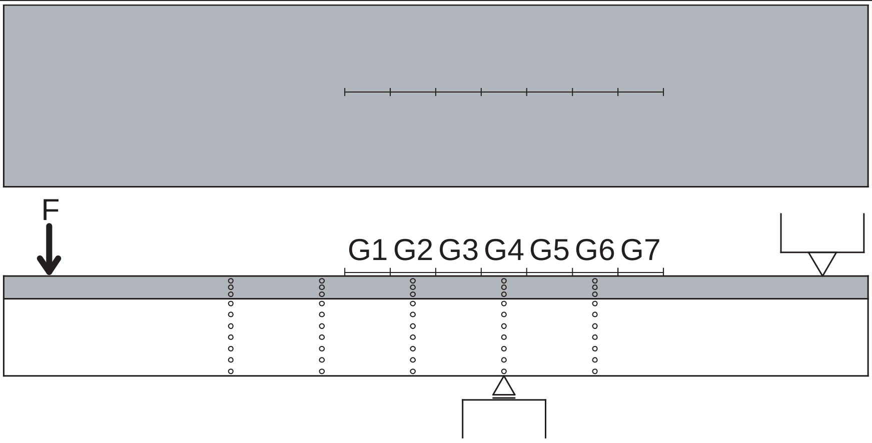
110,377 cycles



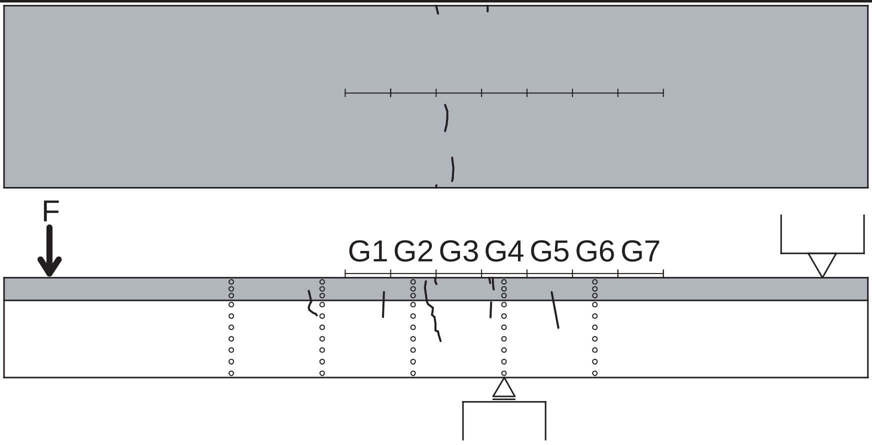
510,486 cycles



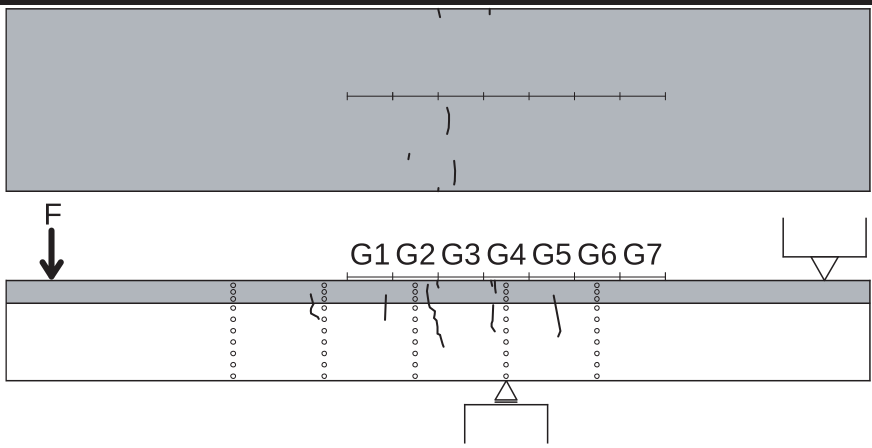
1,010,601 cycles



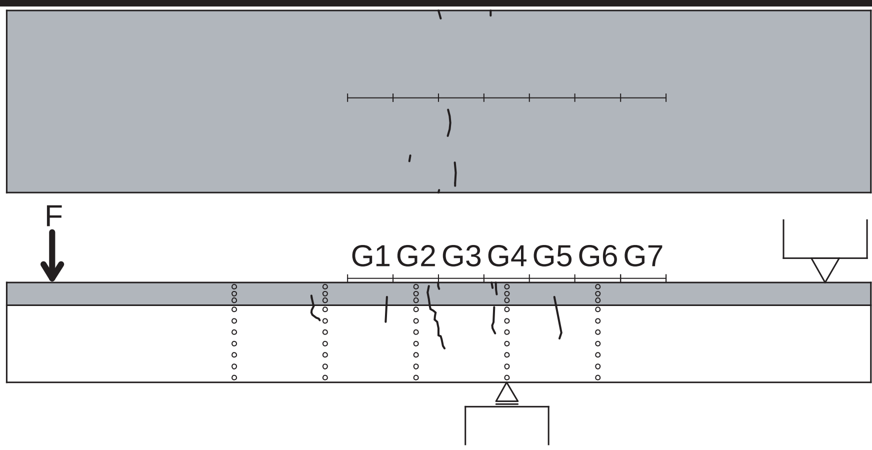
5,004,250 cycles



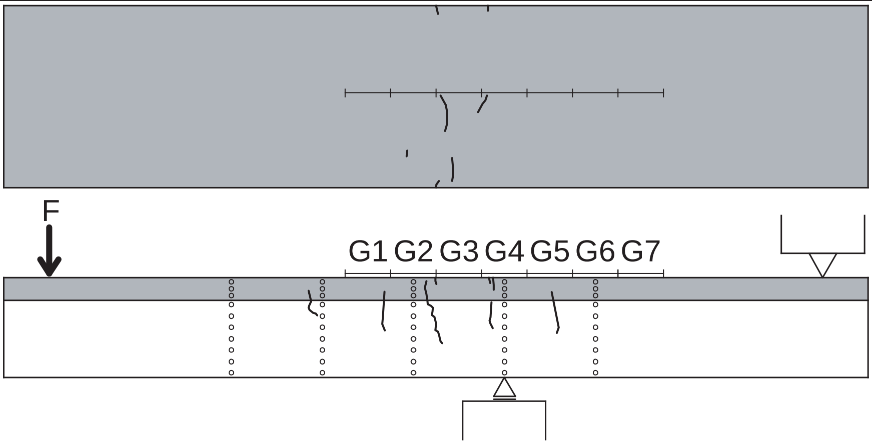
10,004,144 cycles



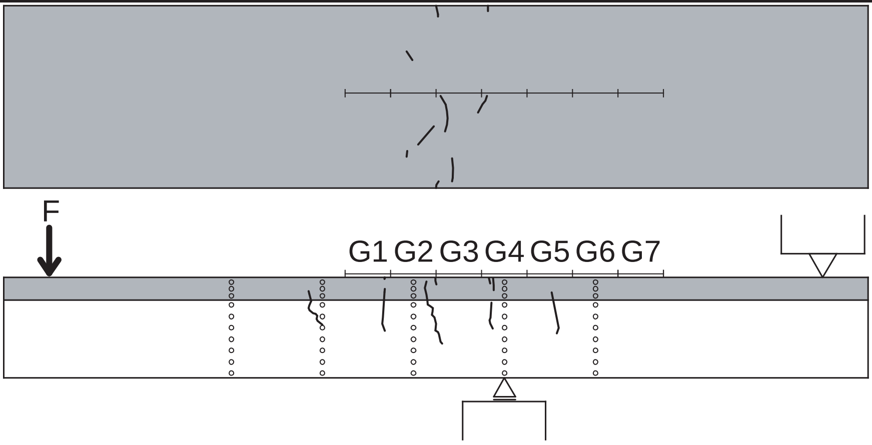
15,004,371 cycles



20,004,489 cycles



23,935,641 cycles



Second fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
49.50 kN	4.95 kN	0.55	10,001,231	run-out

Behaviour of NBF3 test specimen during the second fatigue test

Deflection:

Maximum deflection and deflection range kept approximately constant.

Deformation of R-UHPFRC layer:

Maximum deformation and deformation range at all local zones kept approximately constant.

Deformation over the entire depth of the specimen:

Deformation over the entire depth of the specimen was almost unchanged during the test.

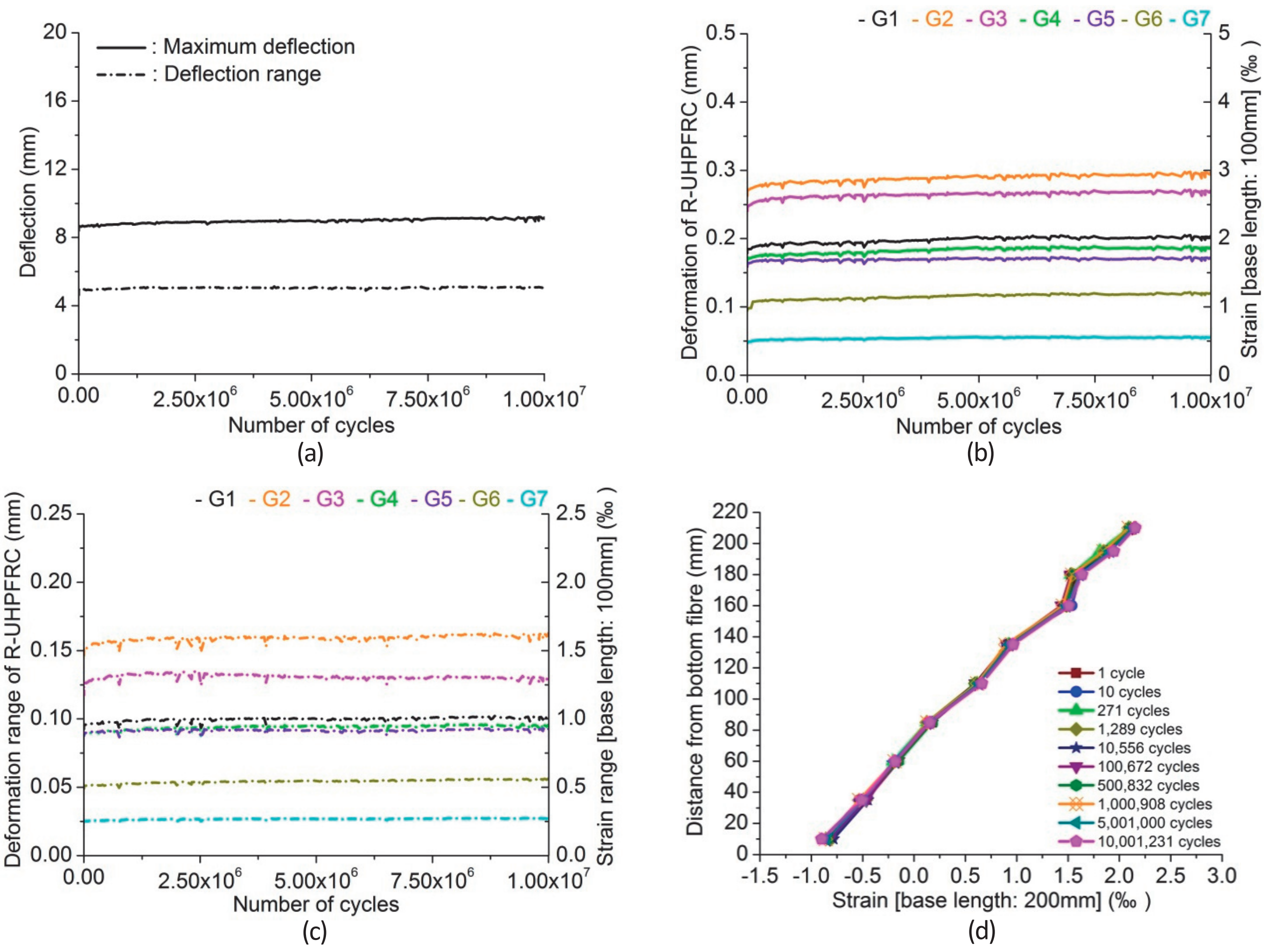


Figure 14 NBF3-ii test: growth curves of (a) maximum deflection and deflection range, (b) maximum deformation of R-UHPFRC layer and (c) its magnified view, (d) deformation range of R-UHPFRC layer and (e) its magnified view and (f) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF3 test specimen during the second fatigue test

<u>271 cycle:</u>

[Top surface of R-UHPFRC layer]

- Diagonal cracks appeared at G3 zone.

<u>100,672 cycles:</u>

[Side of RU-RC beam]

- A diagonal crack crossing the R-UHPFRC – RC interface developed at G7 zone.

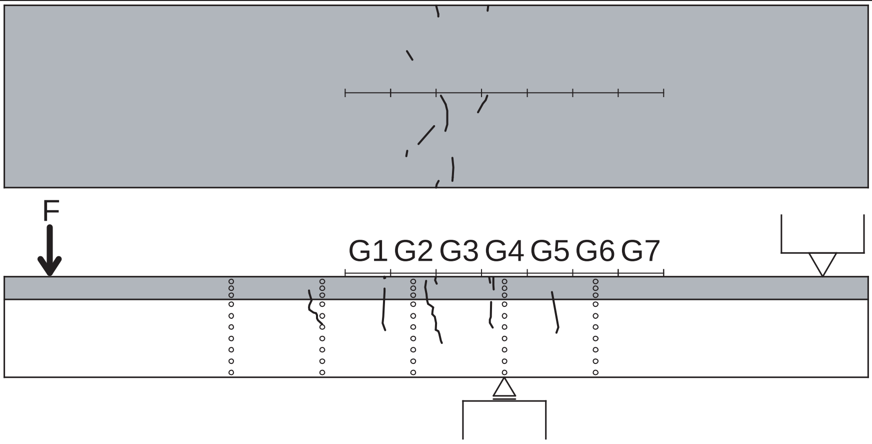
<u>500,832 to 10,001,231 cycles:</u>

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

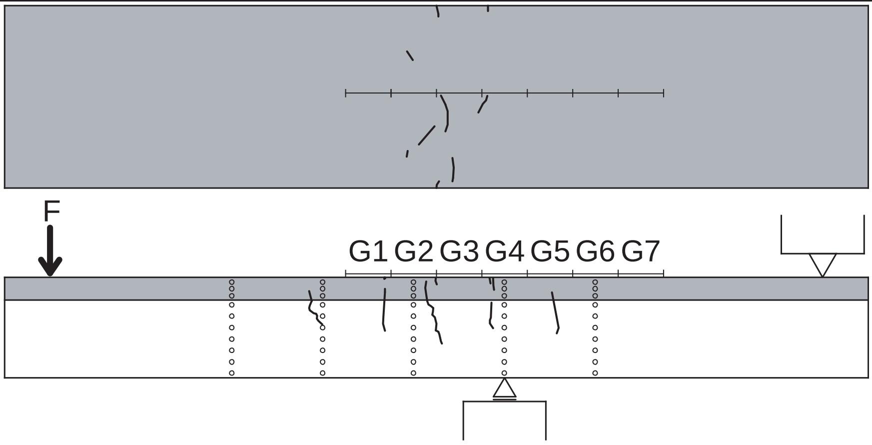
- Although some cracks were caused, all of them weren't relevant to fracture of the specimen.
- Significant change wasn't observed on existing cracks.

Evolution of crack pattern on NBF3 test specimen during the second fatigue test

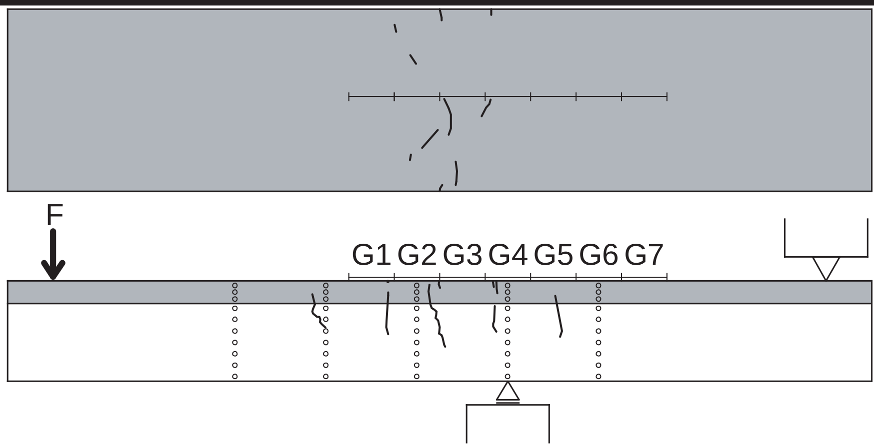
0 cycle



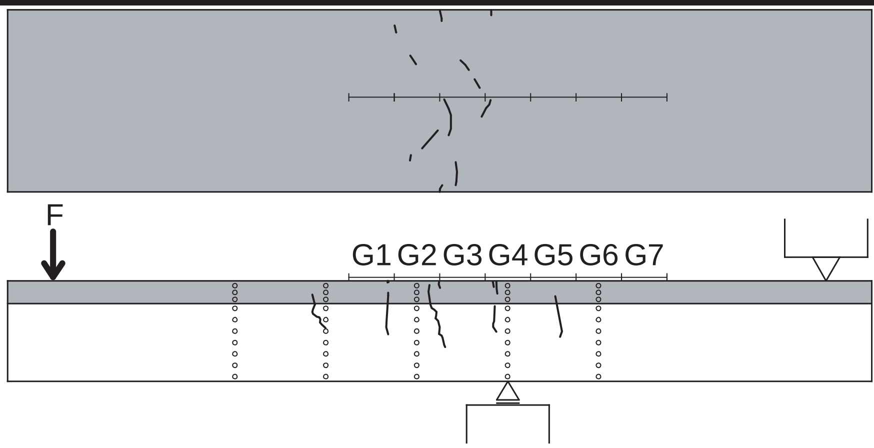
1 cycle



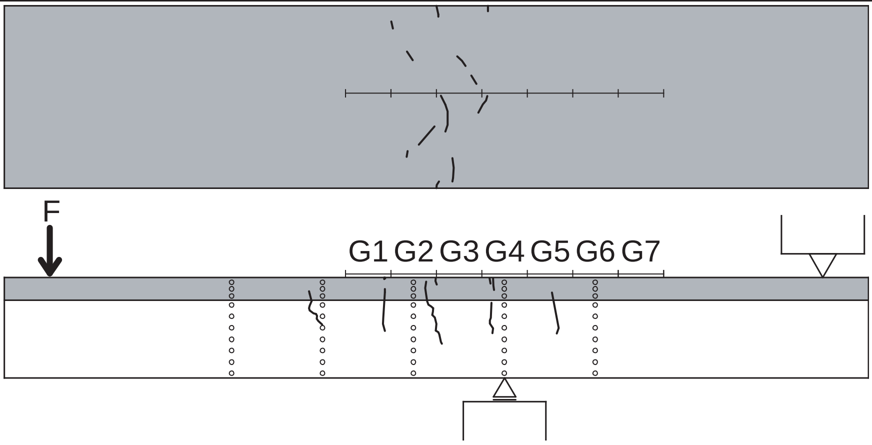
10 cycles



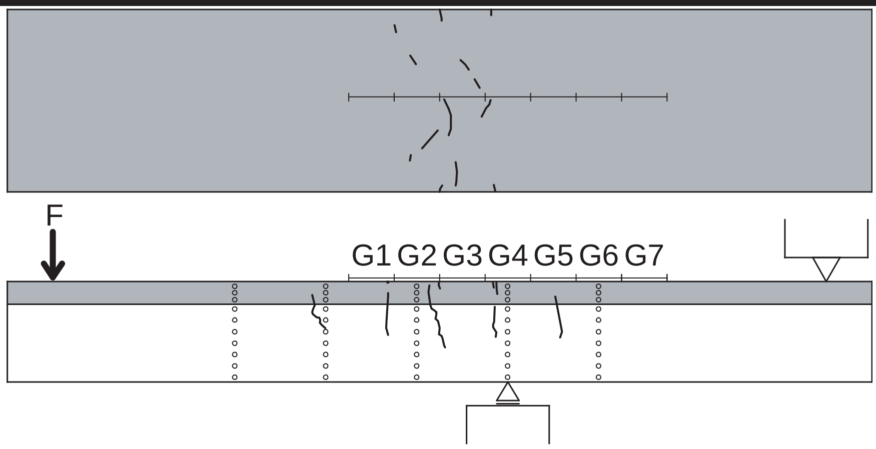
271 cycles



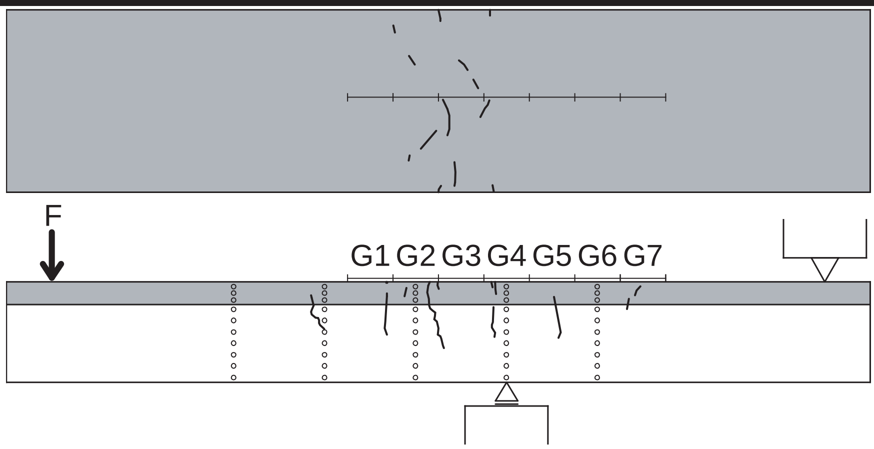
1,289 cycles



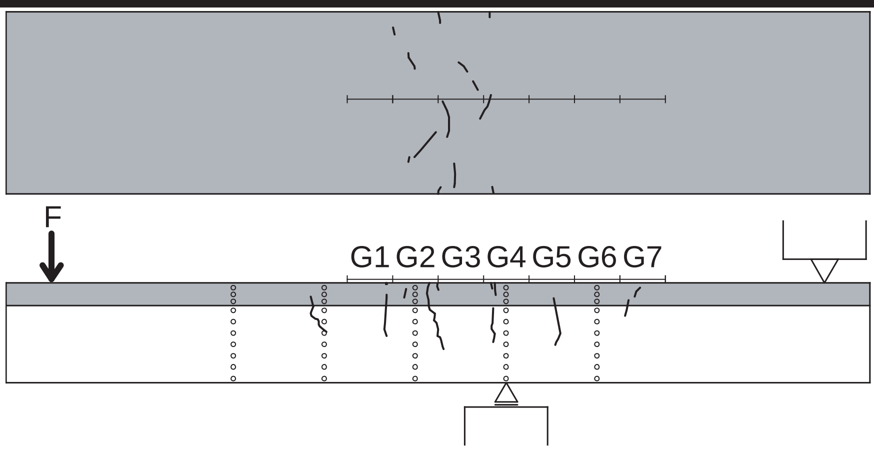
10,556 cycles



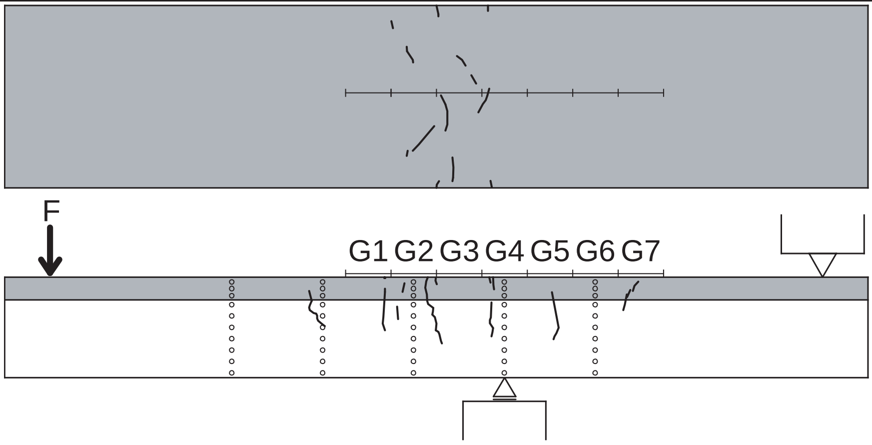
100,672 cycles



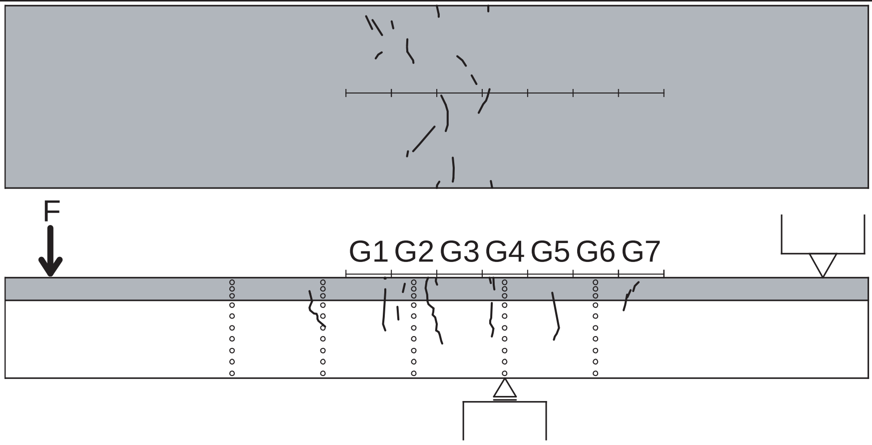
500,832 cycles



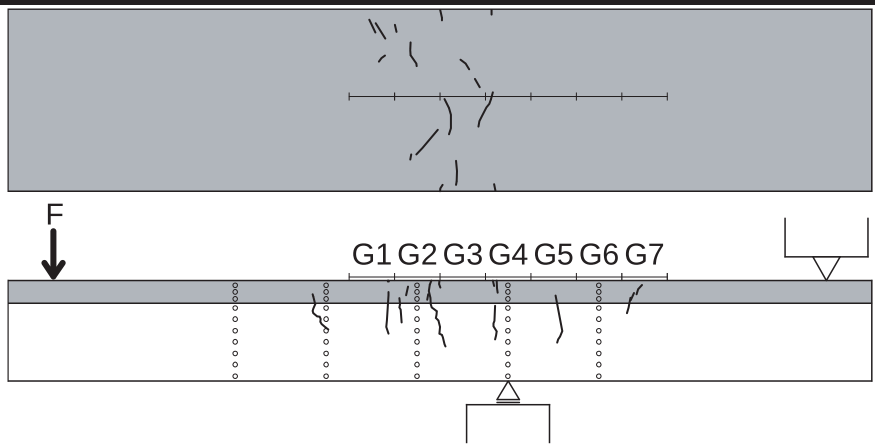
1,000,908 cycles



5,001,000 cycles



10,001,231 cycles



Third fatigue test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
54.00 kN	5.40 kN	0.60	2,095,735	G2 zone

Behaviour of NBF3 test specimen during the third fatigue test

Number of cycles at which steel rebars in R-UHPFRC layer fractured			
First fracture	Second fracture	Third fracture	Final fracture
1,784,500	2,079,200	2,086,200	2,094,600

Deflection:

Maximum deflection kept approximately constant until the first fracture of the four steel rebars in R-UHPFRC layer occurred and then it started to increase. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deflection became larger than before.

Behaviour of deflection range was similar to that of maximum deflection, while its growth rate was always smaller than growth rate of maximum deflection.

Deformation of R-UHPFRC layer:

Maximum deformation behaviour at G2 and G3 zones was similar until the second fracture of the four steel rebars of the R-UHPFRC layer. Maximum deformation at G2 and G3 zones kept almost constant until about736,200 cycles at which maximum local deformation at G2 and G3 zones suddenly rose and then started to increase. When the first fracture of the four steel rebars in the R-UHPFRC layer occurred, growth rate of maximum deformation at G2 and G3 zones significantly increased. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum local deformation at G2 zone became larger than before. Deformation localisation of R-UHPFRC occurred at G2 zone. As for G3 zone, when one of the remaining three reabars in the R-UHPFRC layer fractured, R-UHPFRC at G3 zone softened.

Maximum deformation at the other zones slightly increased until the third facture of the four steel rebars of the R-UHPFRC layer, at which R-UHPFRC at these local zones softened.

Behaviour of deformation range was quite similar to that of maximum deformation at all local zones.

Deformation over the entire depth of the specimen:

Deformation over the entire depth of the specimen was unchanged until 500,842 cycles. On measurements at 1,001,056 cycles, deformation of tension side solely increased, amounting to 1 ‰ strain at top of R-UHPFRC layer.

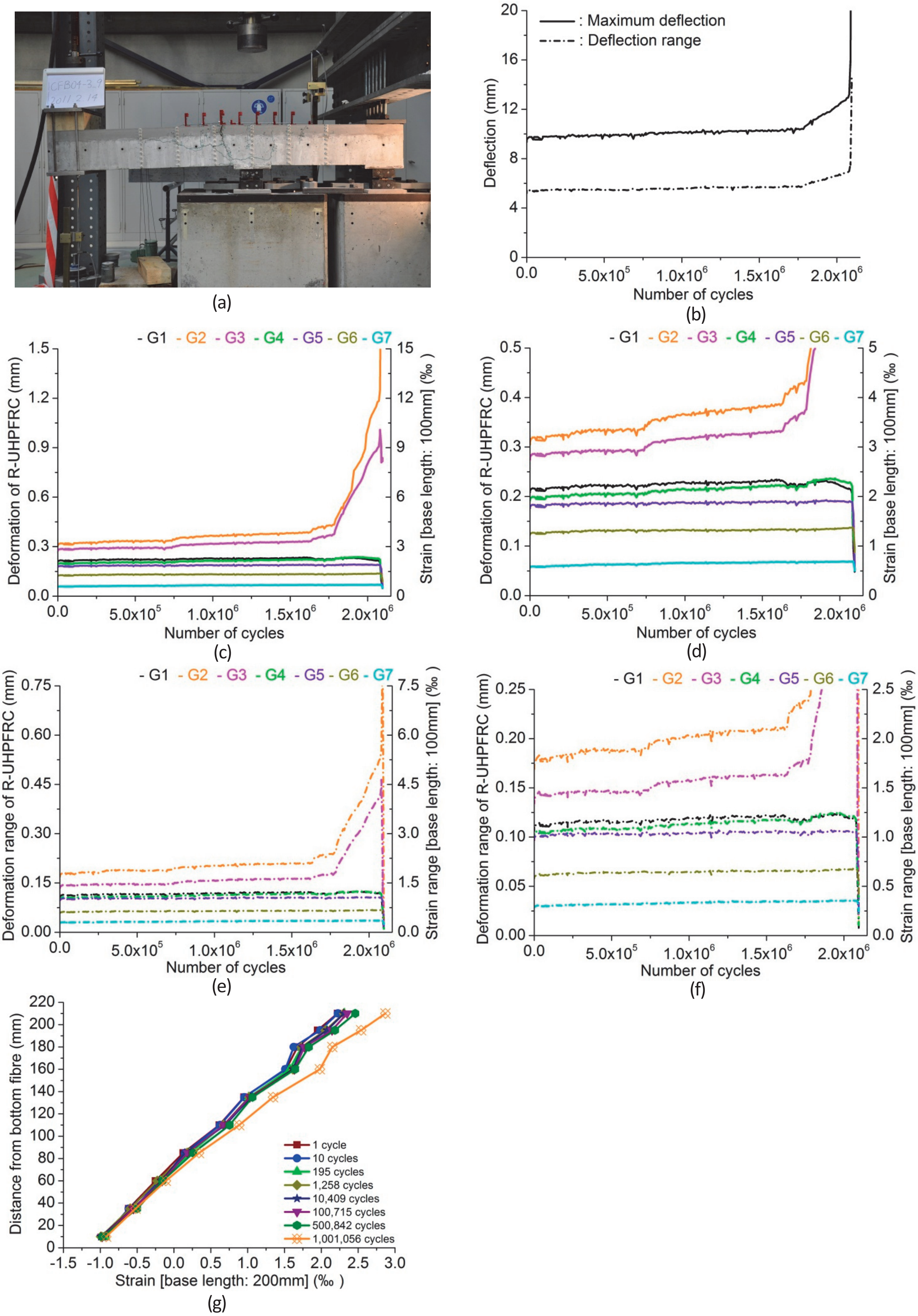


Figure 15 NBF3-iii test: (a) fractured NBF3 test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer and (d) its magnified view, (e) deformation range of R-UHPFRC layer and (f) its magnified view and (g) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF3 test specimen during the third fatigue test

<u>1 cycle:</u>

[Side of RU-RC beam]

- A diagonal crack at G7 zone propagated to bottom of the beam.

<u>10 to 1,001,056 cycles:</u>

[Top surface of R-UHPFRC layer] and [Side of RU-RC beam]

- Significant change was not observed on existing cracks.

<u>Failure (2,095,735 cycles):</u>

[Top surface of R-UHPFRC layer]

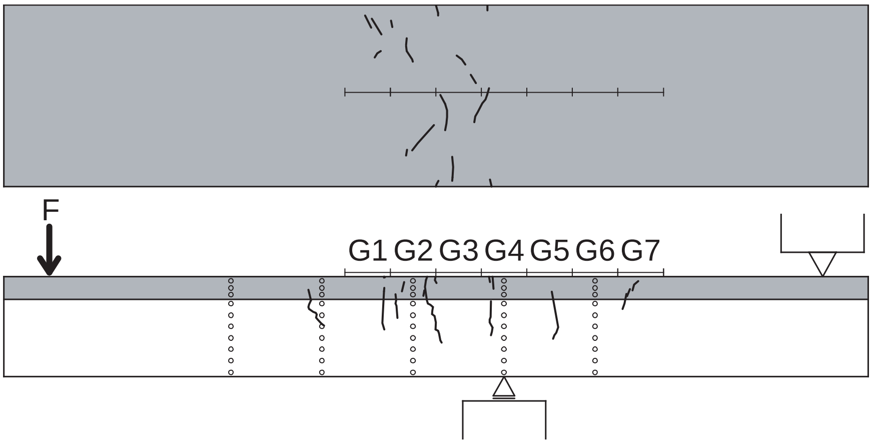
- A fracture crack developed on the G2 – G3 zone border. It was perpendicular to the longitudinal axis of the beam at the transversal half of the beam; at the other half of the beam, the fracture crack curved.
- Most part of the fracture crack was newly caused (it was not formed as coalescence of existing cracks).

[Side of RU-RC beam]

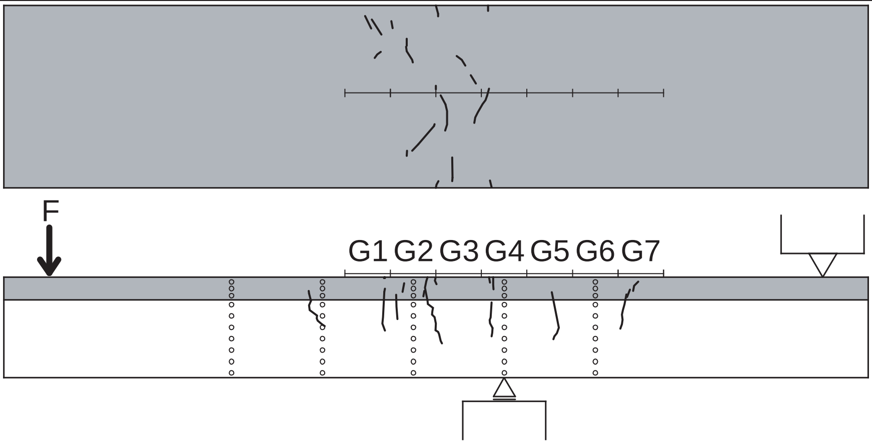
- A fracture crack slightly inclined from vertical axis (called 'vertical fracture crack' hereafter) developed by increasing the width of an existing crack at G2 zone, propagating from top of the R-UHPFRC layer to bottom steel rebars of the RC part.
- Two horizontal and a diagonal fracture cracks were caused in the RC part.
- One fracture horizontal crack propagated from the middle of the vertical fracture crack to cantilever end and joined the diagonal fracture crack. Another horizontal fracture crack propagated from the vertical fracture crack tip to fixed support, approximately running on the position of bottom steel rebars of the RC part.
- A diagonal fracture crack propagated with an angle of about 20˚ against horizontal line from movable support to cantilever end until reaching top steel rebars of the RC part.

Evolution of crack pattern on NBF3 test specimen during the third fatigue test

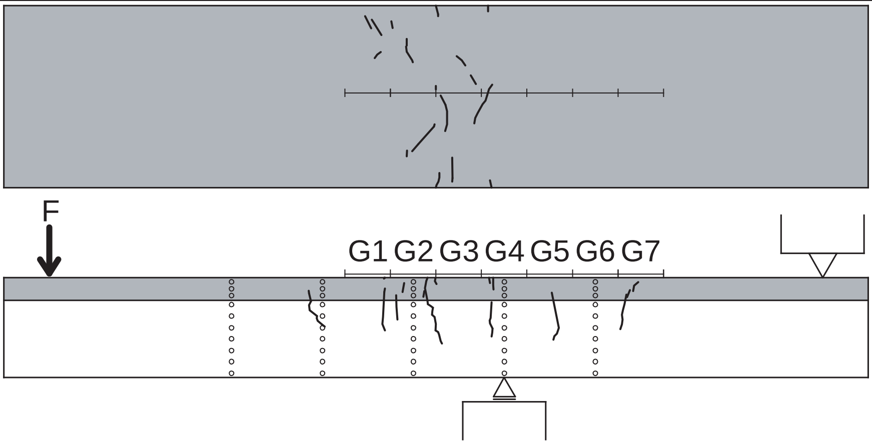
0 cycle



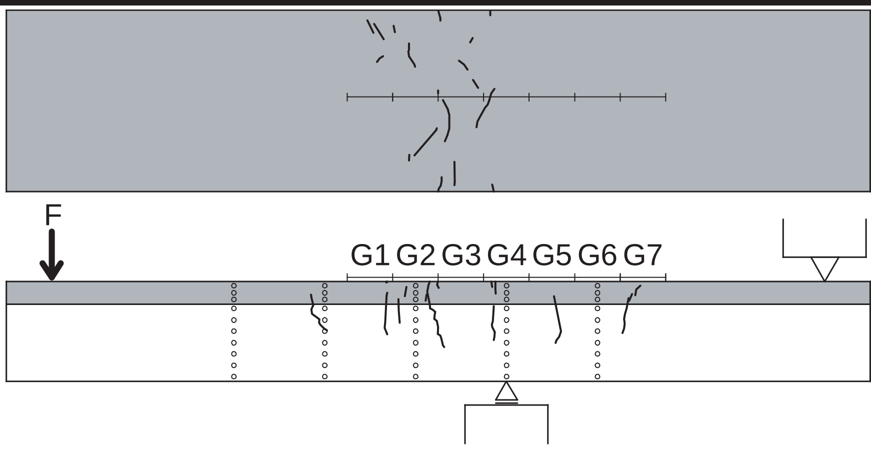
1 cycle



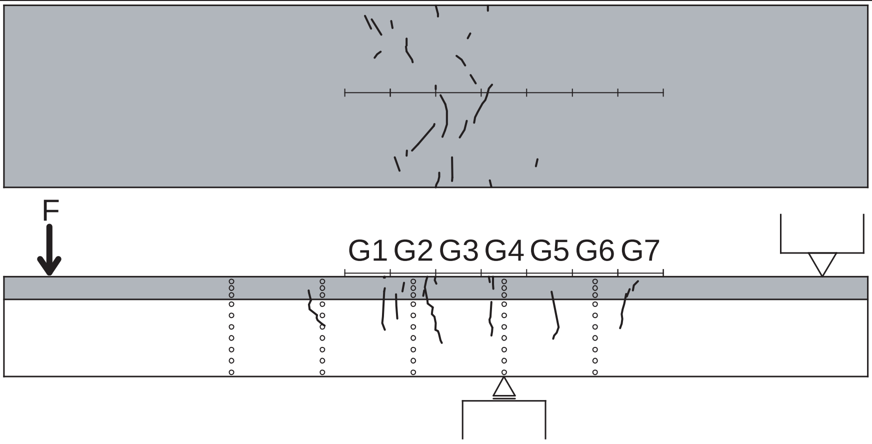
10 cycles



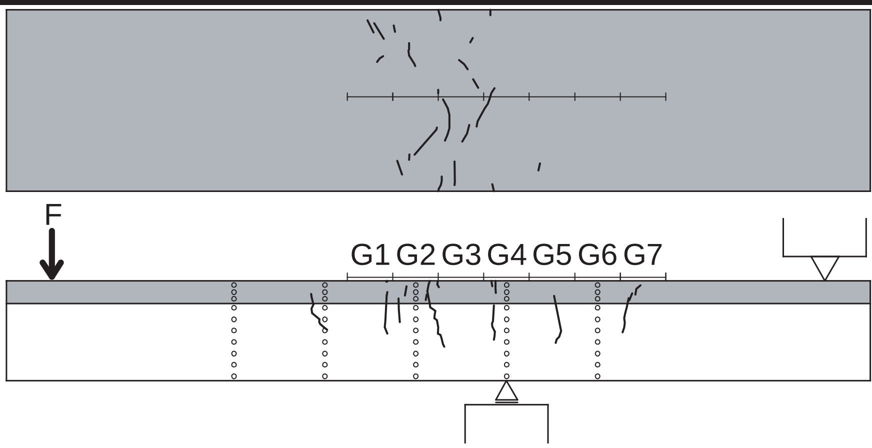
195 cycles



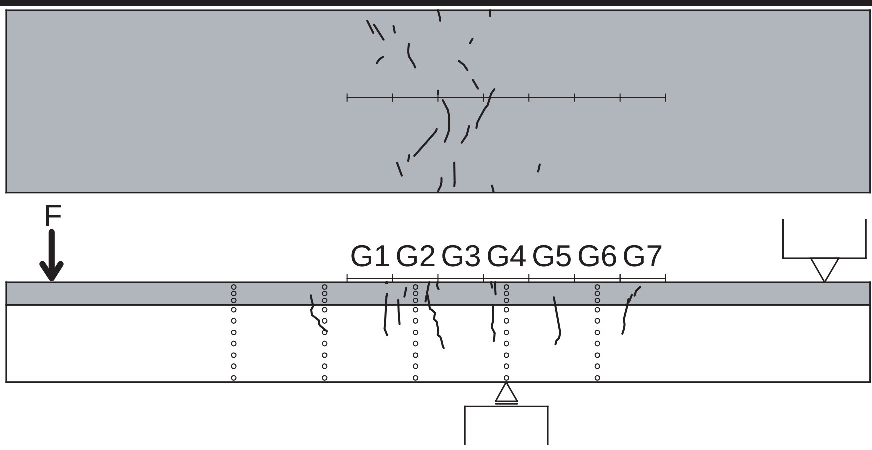
1,258 cycles



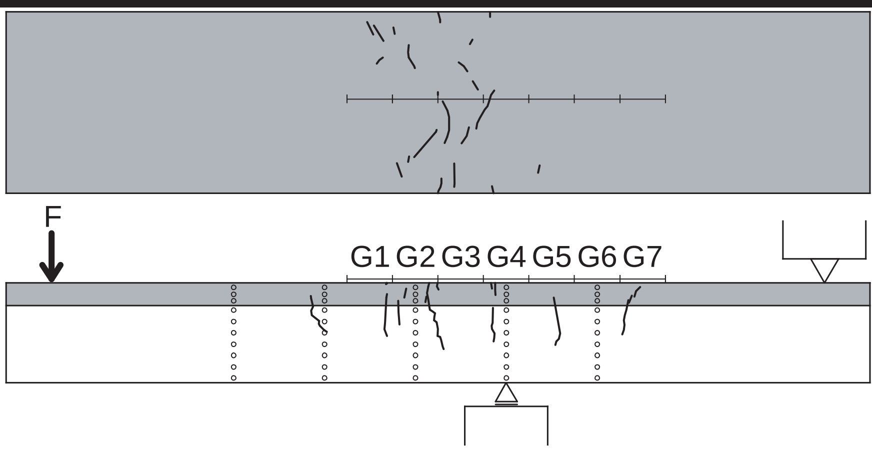
10,409 cycles



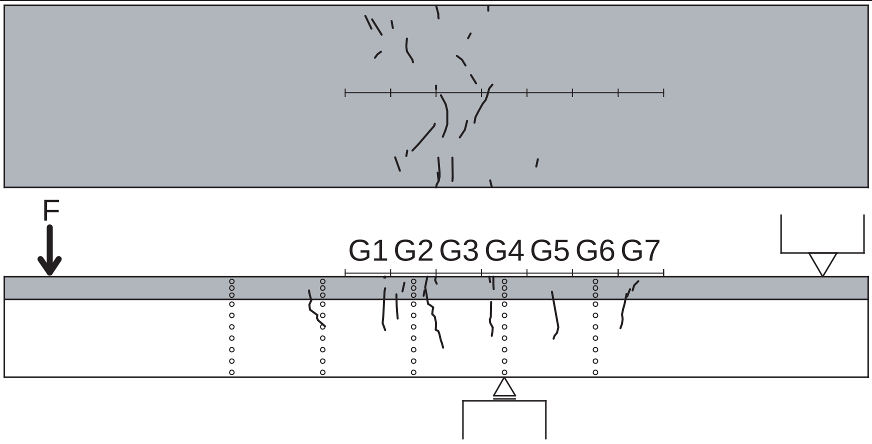
100,715 cycles



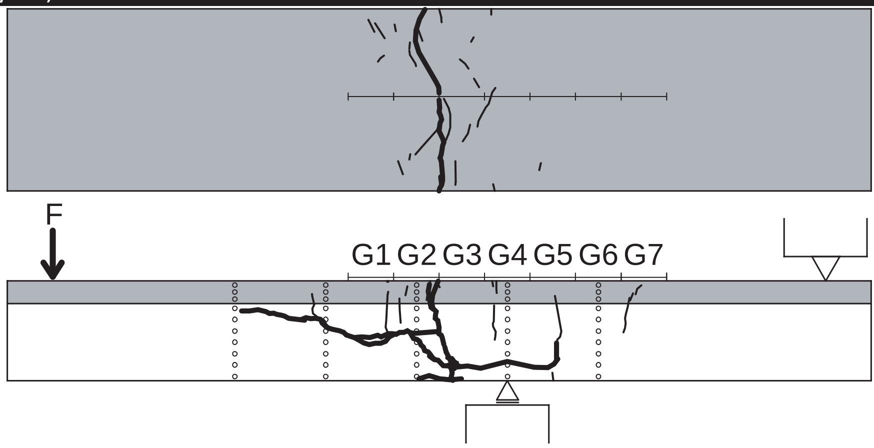
500,842 cycles



1,001,056 cycles



Failure (2,095,735 cycles)



5.4 NBF4 test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
49.50 kN	4.95 kN	0.55	6,986,511	G3 zone

Behaviour of NBF4 test specimen

Number of cycles at which steel rebars in R-UHPFRC layer fractured			
First fracture	Second fracture	Third fracture	Final fracture
6,114,600	6,956,700	6,975,800	6,981,700

<u>Deflection</u>

Maximum deflection rapidly grew during the first 200,000 cycles, followed by moderate increase. When one of the four steel rebars of the R-UHPFRC layer fractured, growth rate of maximum deflection increased slightly. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deflection became larger than before. Maximum deflection continued to increase until the end of the test.

Deflection range rapidly increased during the first 50,000 cycles and then kept approximately constant until the second fracture of the four steel rebars in the R-UHPFRC layer, at which deflection range started to increase drastically.

<u>Deformation of R-UHPFRC layer</u>

At all zones, maximum deformation rapidly grew until 20,000 to 600,000 million cycles, and then its increasing rate became low. Maximum deformation at G3 zone was excessively larger than the other zones. When the first fracture of the four steel rebars in the R-UHPFRC layer occurred, growth rate of maximum deformation at G3 zone significantly increased. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deformation at G3 zone became larger than before. Deformation localisation of R-UHPFRC occurred at G3 zone.

Maximum deformation at G1, G5 and G6 zones increased slightly until the final fracture of the four steel rebars in the R-UHPFRC layer. Maximum deformation at G2 zone increased slightly until the first fracture of the four steel rebars in the R-UHPFRC layer and then it started to decrease. Maximum deformation at G4 zone increased slightly until about 3,757,200 cycles, at which its growth rate started to increase and then returned to the previous level at about 4,291,800 cycles. When the first fracture of the four steel rebars in the R-UHPFRC layer occurred, maximum deformation at G4 zone started to decrease. Maximum deformation at G7 zone kept approximately constant until the final fracture of the four steel rebars in the R-UHPFRC layer.

When the final fracture of the four steel rebars in the R-UHPFRC layer occurred, R-UHPFRC at all zones except G3 zone softened.

Distribution of maximum deformation didn't correspond to distribution of acting moment. Variations were observed on maximum deformation among all zones.

Behaviour of deformation range was quite similar to that of maximum deformation at all local zones.

<u>Deformation over the entire depth of the specimen</u>

Increase of tensile deformation was much larger than that of compressive deformation. Deformation increased at approximately the same rate at every measurement until 501,255 cycles. Deformation at 1,007,009 cycles was almost identical to deformation at 501,255 cycles. Tensile deformation significantly increased between 1,007,009 and 5,009,045 cycles.

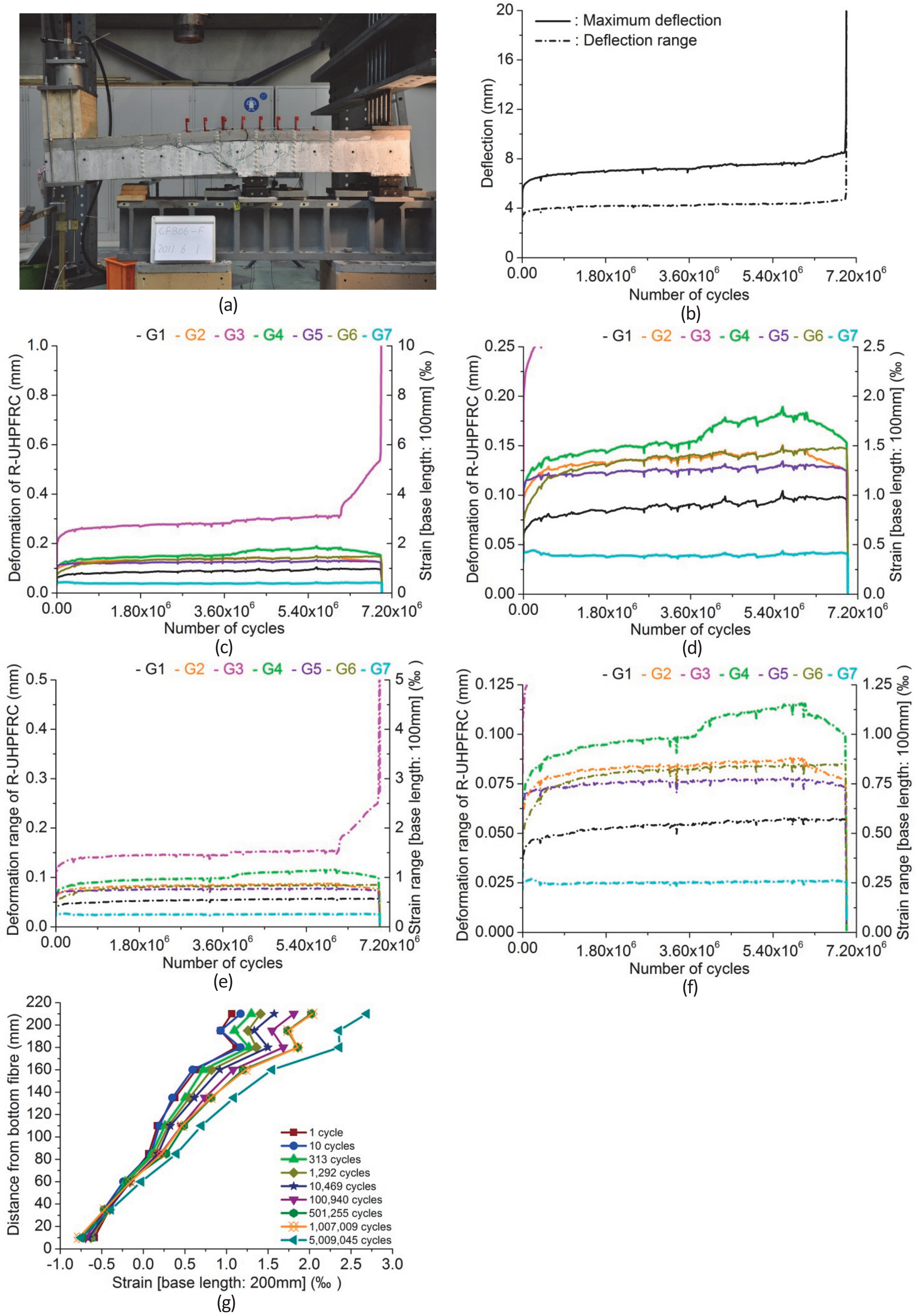


Figure 16 NBF4 test: (a) fractured NBF4 test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer and (d) its magnified view, (e) deformation range of R-UHPFRC layer and (f) its magnified view and (g) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF4 test specimen during the third fatigue test

0 cycle:

[Side of RU-RC beam]

- A horizontal crack was initially observed on the R-UHPFRC – RC interface, extending from G1 to outside of G7 zone.

1 cycle:

[Top surface of R-UHPFRC layer]

- Two short cracks perpendicular to the longitudinal axis of the beam developed at the both edge of the beam at G3 zone.

[Side of RU-RC beam]

- A few vertical cracks developed crossing the R-UHPFRC – RC interface.

313 cycles:

[Side of RU-RC beam]

- A vertical crack was caused at G3 zone in the RC part from the R-UHPFRC – RC interface.
- Existing cracks slightly propagated.

1,292 cycles:

[Top surface of R-UHPFRC layer]

- A short crack perpendicular to the longitudinal axis of the beam appeared close to transversal centre of G3 zone.

10,469 cycles:

[Side of RU-RC beam]

- An existing crack on the G3 – G4 zone border propagated significantly in the RC part.
- Two vertical cracks developed at G5 zone in the R-UHPFRC layer.

100,940 cycles:

[Top surface of R-UHPFRC layer]

- A crack of about 100 mm length approximately perpendicular to the longitudinal axis of the beam developed at G3 zone.

501,255 cycles:

[Top surface of R-UHPFRC layer]

- A long crack coalesced with a short crack at transversal centre of G3 zone.

[Side of RU-RC beam]

- A vertical crack developed crossing the R-UHPFRC – RC interface at G6 zone.

1,007,009 cycles:

[Top surface of R-UHPFRC layer]

- Cracks at G3 zone increased those lengths.

5,009,045 cycles:

[Top surface of R-UHPFRC layer]

- Cracks at G3 zone increased those lengths.

[Side of RU-RC beam]

- A crack on the G3 – G4 zone border propagated in the RC part.
- A vertical crack developed from the R-UHPFRC – RC interface to the RC part at G4 zone.

Failure (6,986,511 cycles):

[Top surface of R-UHPFRC layer]

- A fracture crack approximately perpendicular to the longitudinal axis of the beam appeared at G3 zone. It was formed as coalescence of existing cracks.
- The other existing cracks didn't change.

[Side of RU-RC beam]

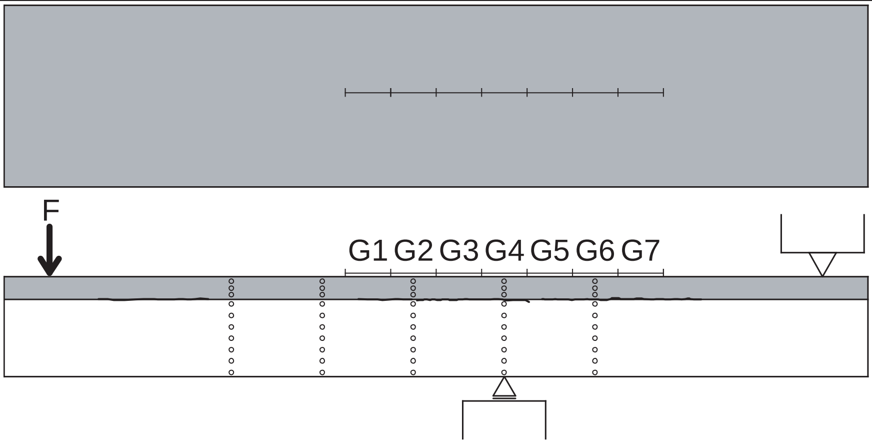
- A vertical fracture crack developed by increasing the width of an existing crack on the G3 – G4 zone border in the R-UHPFRC layer.
- A fracture crack appeared on the R-UHPFRC – RC interface, extending from G2 zone to G4 zone.
- A diagonal fracture crack propagated with an angle of about 20° against horizontal line from movable support to cantilever end until reaching the R-UHPFRC – RC interface. Concrete was significantly crushed at the tip of the diagonal fracture crack

in compression.

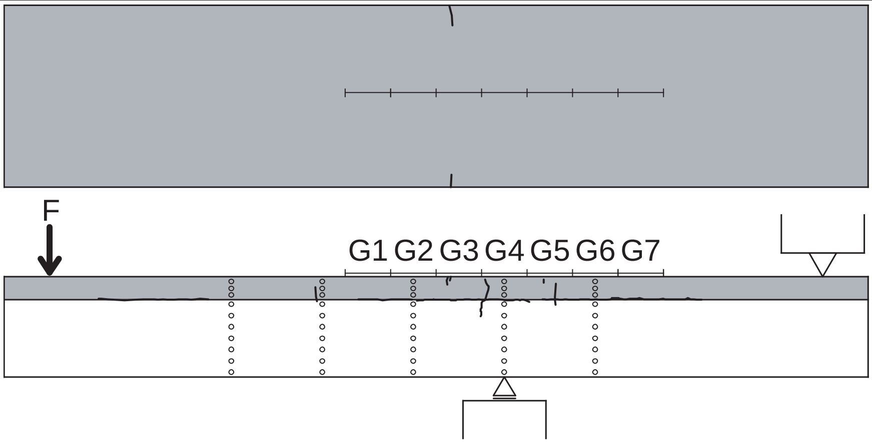
- A few diagonal cracks with an angle of about 20° against horizontal line developed toward fixed support.
- Two vertical cracks appeared at G2 zone in the RC part.

Evolution of crack pattern on NBF4 test specimen

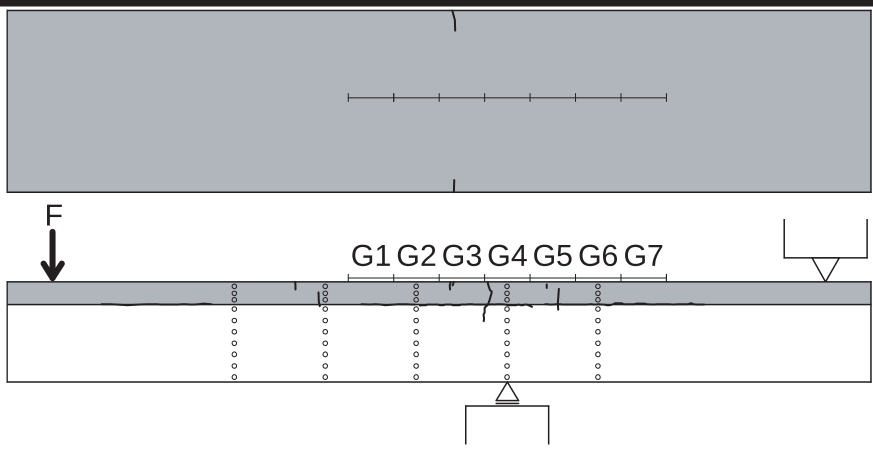
0 cycle



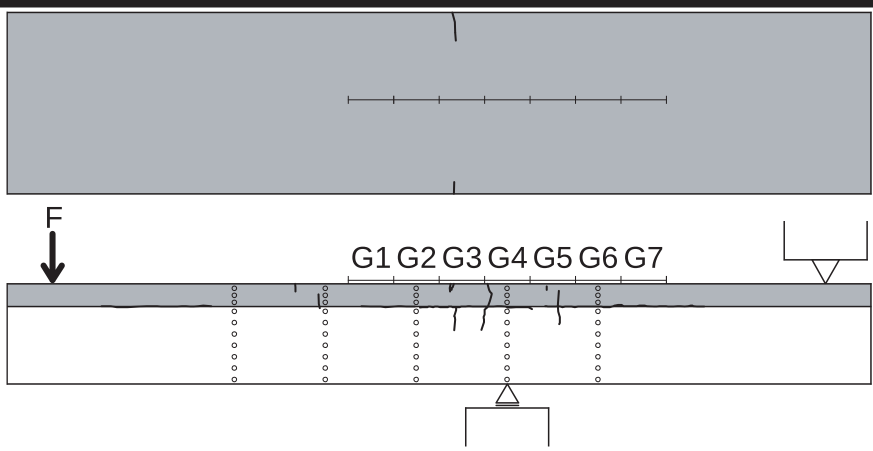
1 cycles



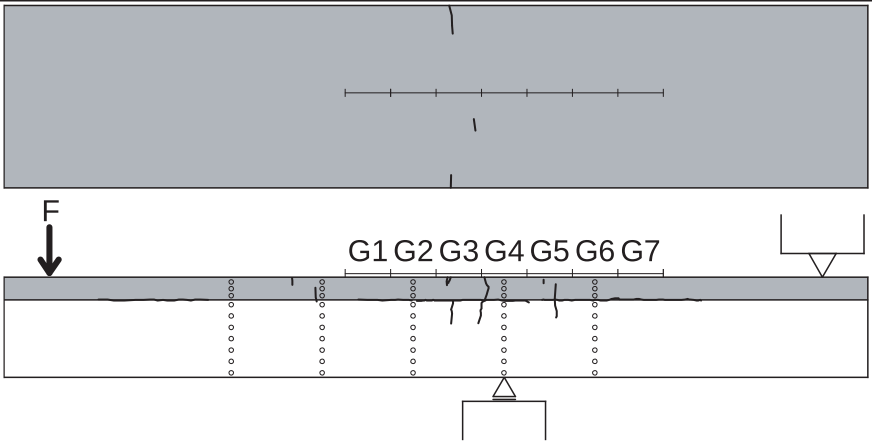
10 cycles



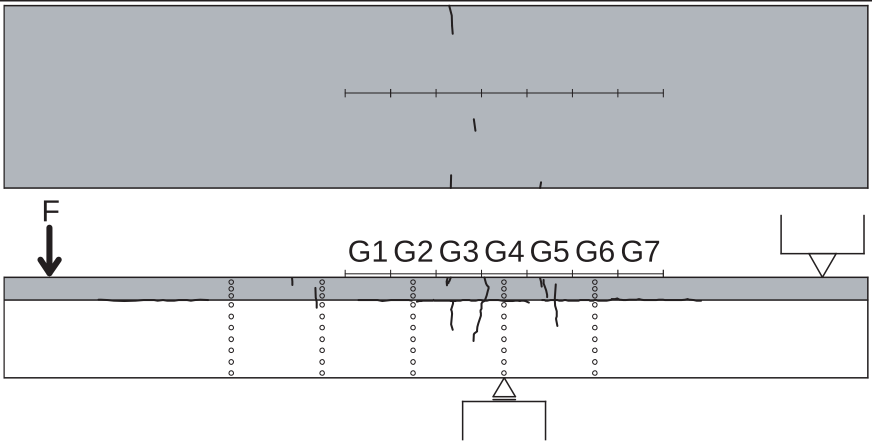
313 cycles



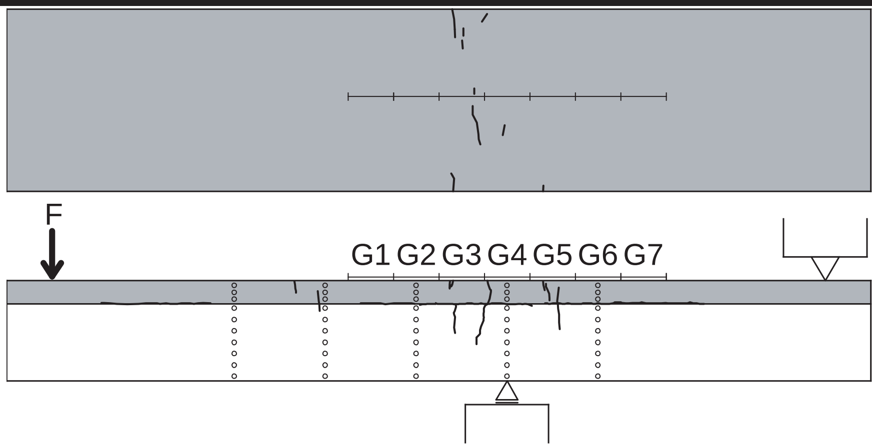
1,292 cycles



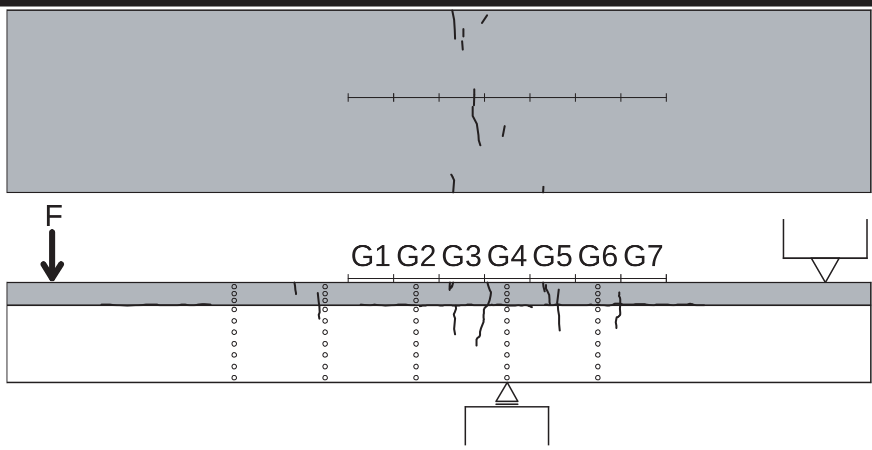
10,469 cycles



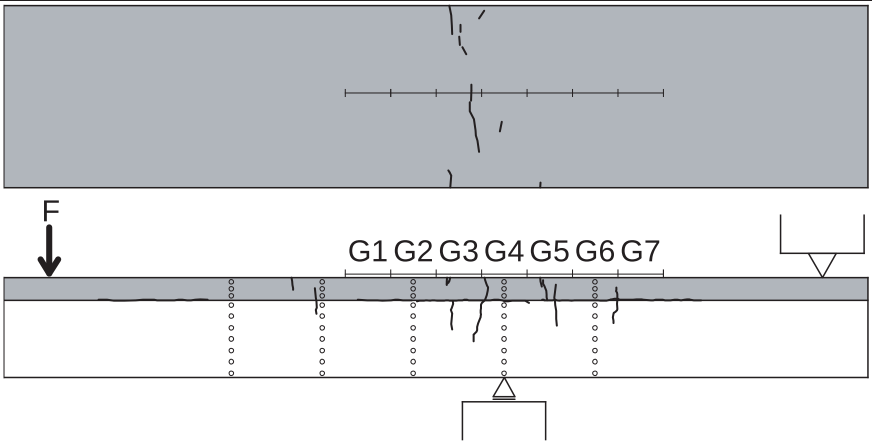
100,940 cycles



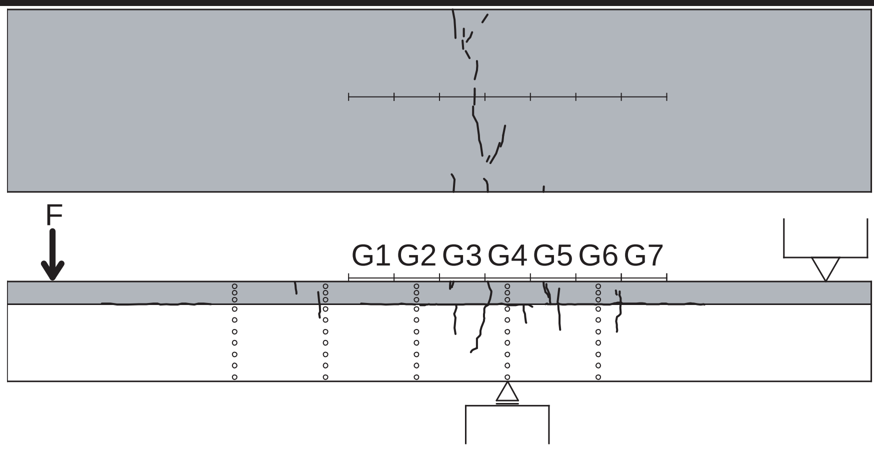
501,255 cycles



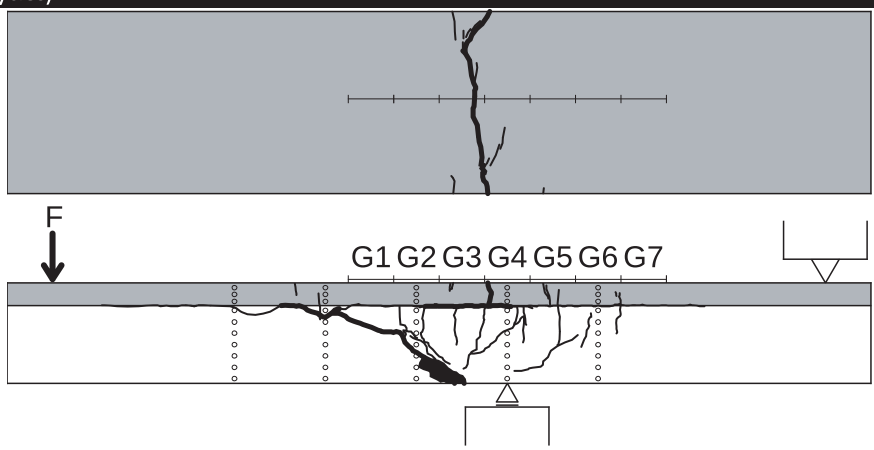
1,007,009 cycles



5,009,045 cycles



Failure (6,986,511 cycles)



5.5 NBF5 test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation in R-UHPFRC
49.50 kN	4.95 kN	0.55	999,226	G2 ozne

NBF5 test specimen behaviour during the fatigue test

Number of cycles at which steel rebars in R-UHPFRC layer fractured			
First fracture	Second fracture	Third fracture	Final fracture
877,700	969,400	990,000	994,840

Deflection

Maximum deflection rapidly grew during the first 15,000 cycles and then continued to increase with much smaller growth rate than before. When one of the four steel rebars in R-UHPFRC layer fractured, maximum deflection growth rate increased slightly. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deflection became larger than before. Maximum deflection continued to increase until the end of the test.

Deflection range rapidly increased during the first 2,000 cycles and then kept approximately constant until the fracture of the final steel rebars in the R-UHPFRC layer, at which deflection range started to increase significantly.

Deformation of R-UHPFRC layer

Maximum deformation at all local zones except G2 and G7 zones rapidly grew during the first 20,000 cycles and then continued to increase with much smaller growth rate than before. Maximum deformation at G2 zone gradually increased, while maximum deformation at G7 zone kept almost constant.

Although reading of maximum deformation at G2 zone was the second smallest among all zones, when one of the four steel rebars in R-UHPFRC layer fractured, its growth rate significantly increased and it became the largest among all zones. Afterwards, each time one of the remaining three steel rebars in the R-UHPFRC layer fractured, growth rate of maximum deformation at G2 zone became larger than before. Deformation localisation of R-UHPFRC occurred at G2 zone.

Maximum deformation at G1 and G3 zones suddenly rose slightly when one of the four steel rebars in the R-UHPFRC layer fractured, and soon it started to decrease. At the second fracture of the remaining three steel rebars in the R-UHPFRC layer, R-UHPFRC at G1 and G3 zones softened. When the first fracture of the four steel rebars in the R-UHPFRC occurred, maximum deformation at G4 zone started to decrease and as the number of cycles increased, its decrease rate gradually increased. When the final steel rebar in the R-UHPFRC layer fractured, R-UHPFRC at G4 to G7 zones softened.

Distribution of maximum deformation didn't correspond to distribution of acting moment. Variations were observed on maximum deformation among all zones.

Behaviour of deformation range at all local zones was quite similar to that of maximum deformation.

Deformation over the entire depth of the specimen

Deformation over the entire depth of the specimen increased with approximately constant growth rate at every measurement from 10 to 501,850 cycles. Increase of tensile deformation was much larger than that of compressive deformation.

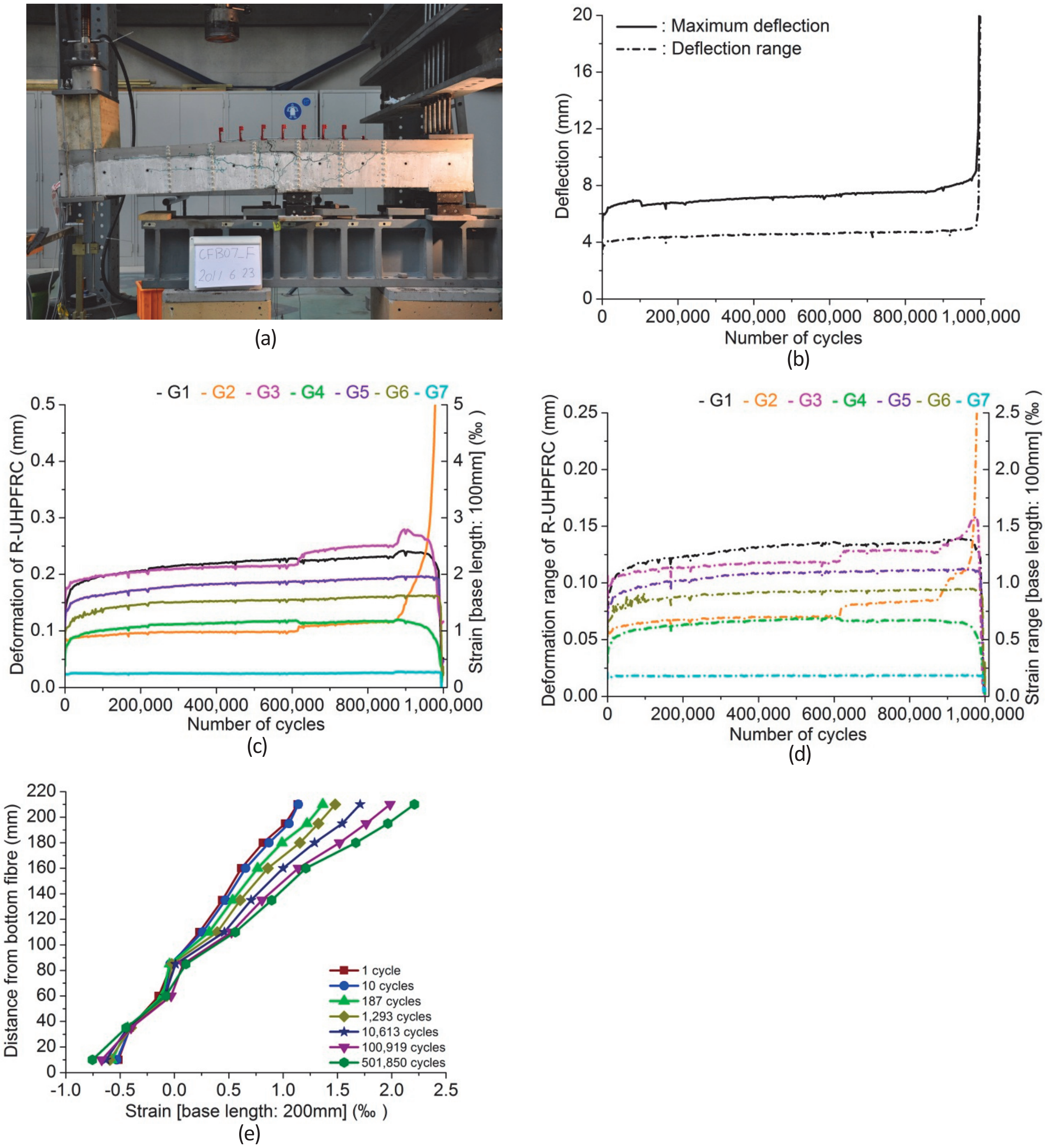


Figure 17 NBF5 test: (a) fractured NBF5 test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer, (d) deformation range of R-UHPFRC layer and (e) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of NBF5 test specimen

0 cycle:

[Side of RU-RC beam]

- A horizontal crack was initially observed on the R-UHPFRC – RC interface, extending from G1 zone to fixed support.

1 cycle:

[Side of RU-RC beam]

- Several short vertical cracks developed in the R-UHPFRC layer and RC part.

10 cycles:

[Side of RU-RC beam]

- A medium-length vertical crack was caused outside G1 zone crossing the R-UHPFRC – RC interface, while existing cracks slightly increased those lengths.

187 cycles:

[Top surface of R-UHPFRC layer]

- Two short cracks almost perpendicular to the longitudinal axis of the beam developed at the both edge of the beam at G3 zone and outside of G1 zone.

[Side of RU-RC beam]

- Existing cracks slightly increased those lengths.

1,293 cycles:

[Top surface of R-UHPFRC layer]

- A rather long crack with an angle of 15˚ from transversal axis of the beam appeared at G5 zone.

[Side of RU-RC beam]

- A few short vertical cracks developed close to top surface of the beam at G3 zone in the R-UHPFRC layer.
- A vertical crack at outside of G1 zone increased its length in the RC part.

10,613 cycles:

[Top surface of R-UHPFRC layer]

- A few cracks of medium length approximately perpendicular to the longitudinal axis of the beam appeared.

100,919 cycles:

[Top surface of R-UHPFRC layer]

- Several short cracks were caused in a small area close to an edge of the beam at G2 and G3 zones.
- A rather long crack with an angle of 15˚ from transversal axis of the beam appeared at G2 zone.

[Side of RU-RC beam]

- A few vertical cracks developed at G2 and G3 zones in the R-UHPFRC layer and the RC part.
- Existing cracks increased those lengths. Especially, a vertical crack at G3 zone in the RC part grew significantly.

501,850 cycles:

[Top surface of R-UHPFRC layer]

- Two cracks almost perpendicular to the longitudinal axis of the beam developed at G2 zone.
- Significant change wasn't observed on existing cracks.

[Side of RU-RC beam]

- A short vertical crack developed at G4 zone in the R-UHPFRC layer.
- An existing vertical crack at G4 zone in the RC part increased its length significantly.
- The other existing cracks didn't show remarkable change.

Failure (999,226 cycles):

[Top surface of R-UHPFRC layer]

- A fracture crack developed on the G2 – G3 zone border and was perpendicular to the longitudinal axis of the beam.
- Most part of the fracture crack was newly caused.

[Side of RU-RC beam]

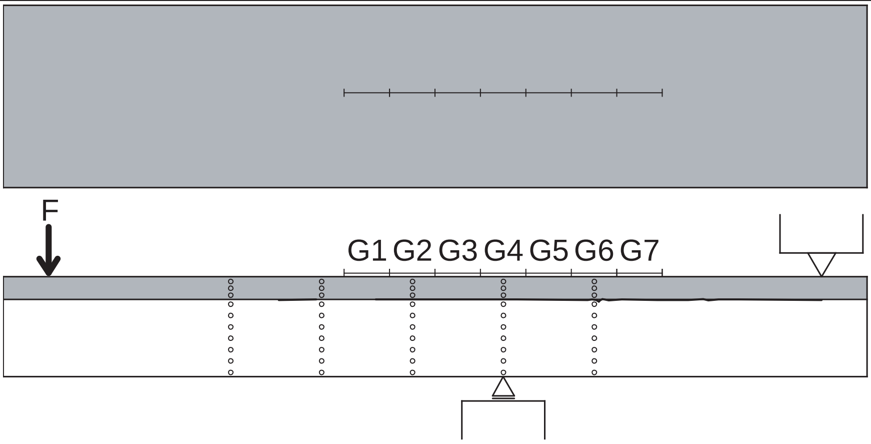
- A vertical fracture crack appeared at G3 zone in the R-UHPFRC layer by increasing the width of an existing crack.
- On the R-UHPFRC – RC interface between G2 to G4 zone, a horizontal fracture crack appeared. From the tip of the

horizontal fracture crack at G2 zone, a vertical fracture crack developed in the RC part by increasing the width of an existing crack. From the bottom tip of the vertical fracture crack, a diagonal fracture crack propagated with an angle of about 10° against horizontal line towards cantilever end until reaching the R-UHPFRC – RC interface at outside of G1 zone.

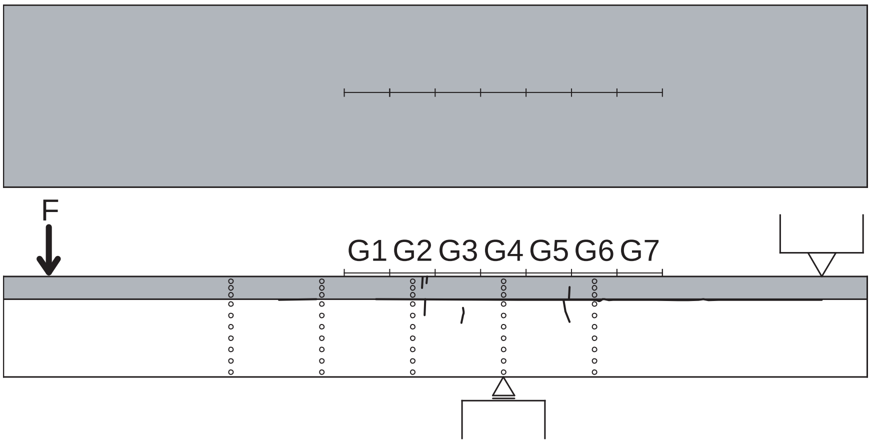
- A fracture crack developed approximately on the position of top steel rebars in the RC part from G4 to G6 zone.
- Several vertical and diagonal cracks were caused at G3 zone in the RC part.
- A diagonal crack with an angle of about 20° against horizontal line developed from movable support until reaching the R-UHPFRC – RC interface at outside of G7 zone.

Evolution of crack pattern on NBF5 test specimen

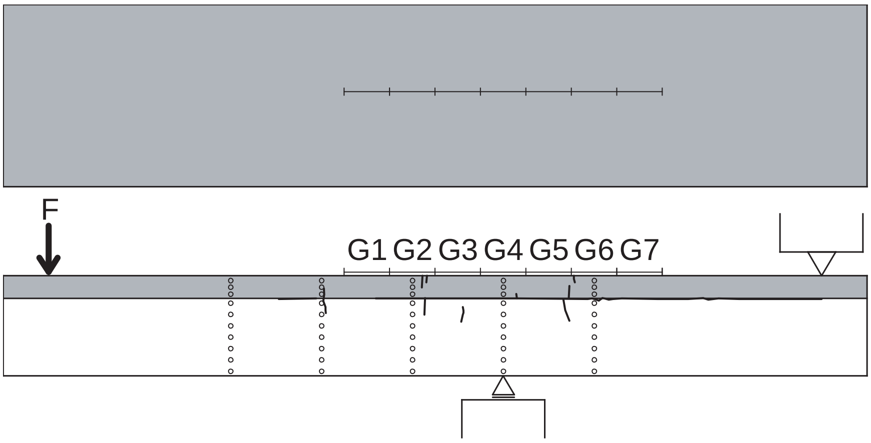
0 cycle



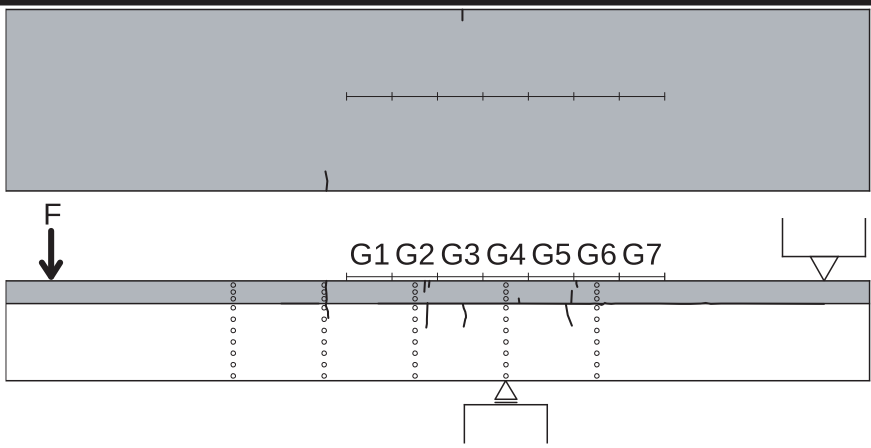
1 cycles



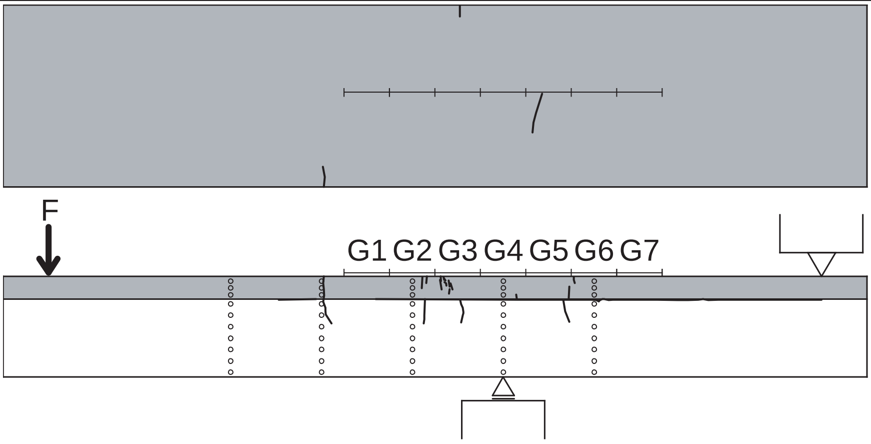
10 cycles



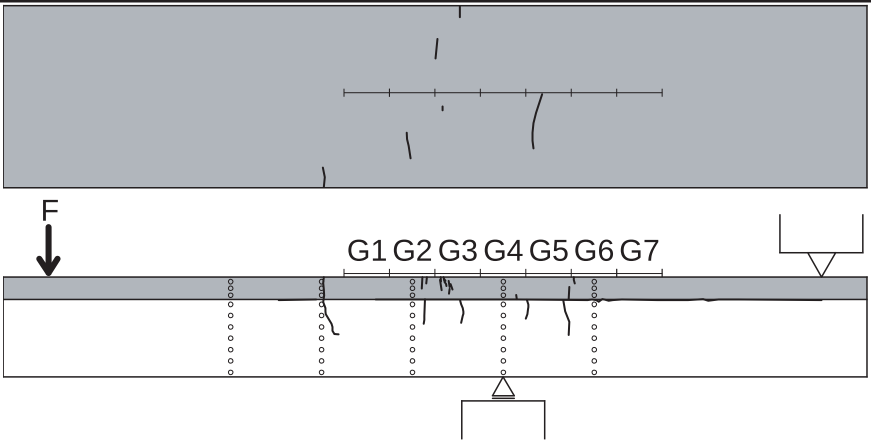
187 cycles



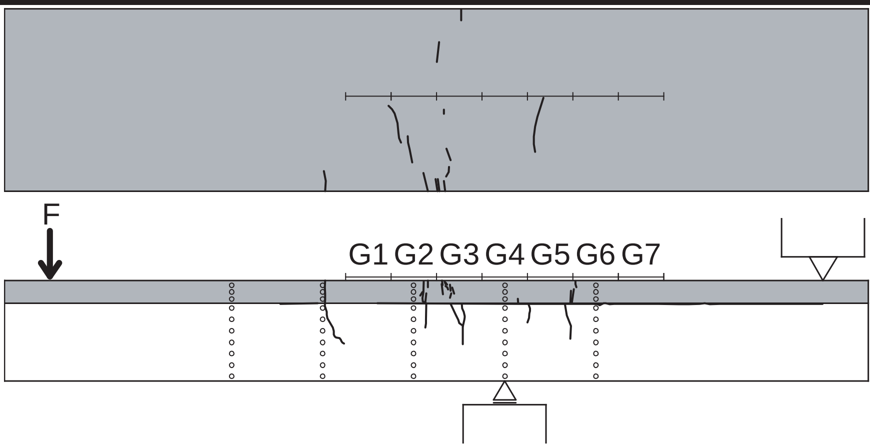
1,293 cycles



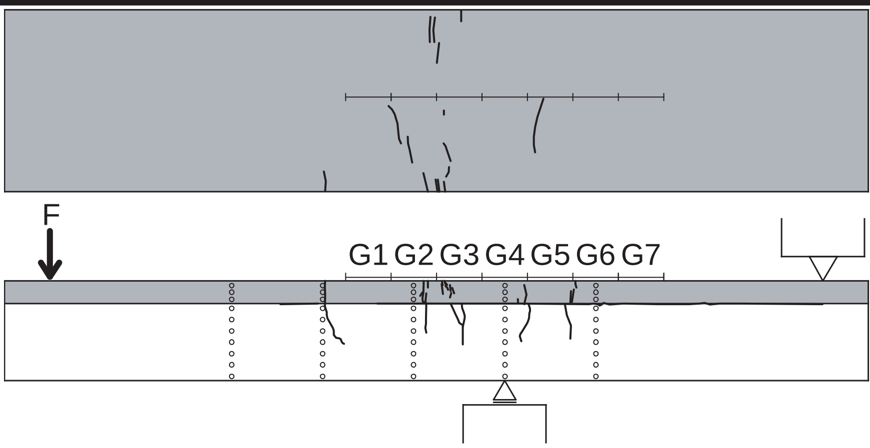
10,613 cycles



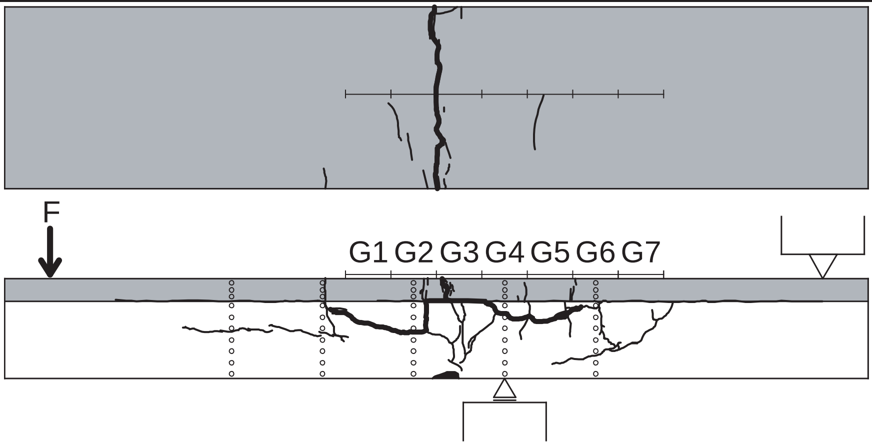
100,919 cycles



501,850 cycles



Failure (999,226 cycles)



5.6 RC test

Test parameters and results

F_{max} [kN]	F_{min} [kN]	F_{max}/F_u	N	Deformation localisation
25.00 kN	2.50 kN	0.50	359,340	G3 zone

RC test specimen behaviour during the fatigue test

Number of cycles at which top steel rebars fractured			
First fracture	Second fracture	Third fracture	Final fracture
328,100	344,300	358,742	358,883

Deflection

Maximum deflection gradually increased during the first 35,000 cycles and then kept more or less constant. When one of four top steel rebars fractured, maximum deflection growth rate increased. Afterwards, each time one of the remaining three top steel rebars fractured, growth rate of maximum deflection became larger than before. Maximum deflection continued to increase until the end of the test.

Behaviour of deflection range was approximately similar to that of maximum deflection.

Deformation of R-UHPFRC layer

Maximum deformation at G3 zone kept roughly constant. When one of the four top steel rebars fractured, maximum deformation at G3 zone suddenly rose by about 0.2 mm and then gradually increased. When one of the remaining three top steel rebars fractured, maximum deformation at G3 zone rose by about 0.5 mm and then gradually increased with higher growth rate than before. When the third fracture of the four top steel rebars occurred, maximum deformation at G3 zone rose significantly. Soon after that, the final fracture of the four top steel rebars occurred and then G3 displacement transducer reached its upper measurement limit.

Maximum deformation at G5 zone rapidly increased until about 25,500 cycles and then kept approximately constant. At about 152,000 cycles, maximum deformation at G5 zone suddenly rose by about 0.03 mm and then kept approximately constant again. When the second fracture of the four top steel rebars occurred, maximum deformation at G5 zone sharply decreased by about 0.03 mm. When the final fracture of the four top steel rebars occurred, concrete at G5 zone softened.

Maximum deformation at G1 and G7 zones kept approximately constant until the second fracture of the four top steel rebars at which readings of maximum deformation at G1 and G7 zone slightly decreased. When the final fracture of the four top steel rebars occurred, concrete at G1 and G7 zone softened.

Maximum deformation at G2 zone kept roughly constant, while maximum deformation at G4 zone gradually increased. When one of the four top steel rebars fractured, maximum deformation at G2 and G4 zones suddenly decreased. Afterwards, each time one of the remaining three top steel rebars fractured, maximum deformation at G2 and G4 zones decreased.

Maximum deformation at G6 zone kept more or less constant from the beginning to the end of the test.

Behaviour of deformation range at all zones was approximately similar to that of maximum deformation.

Deformation over the entire depth of the specimen

Deformation over the entire depth of the specimen significantly increased between 10 and 182 cycles and then grew with approximately constant growth rate at every measurement from 182 to 100,481 cycles. Increase of tensile deformation was larger than that of compressive deformation.

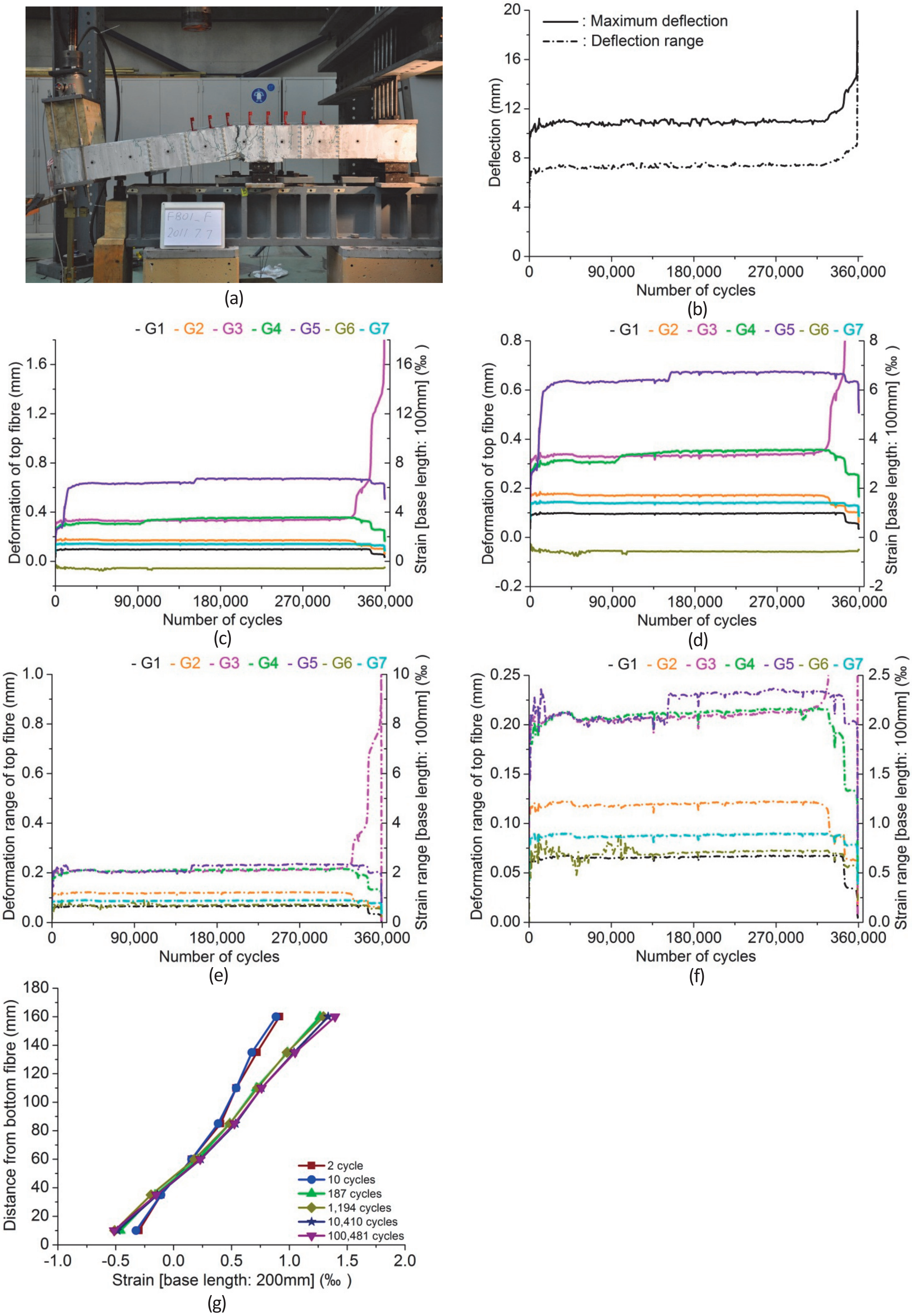


Figure 18 RC test: (a) fractured RC test specimen, growth curves of (b) maximum deflection and deflection range, (c) maximum deformation of R-UHPFRC layer, (d) deformation range of R-UHPFRC layer and (e) growth of maximum strain at column 3 over the entire depth of the specimen

Cracking behaviour of RC specimen

2 cycles:

[Top surface of RC beam]

- Several cracks approximately perpendicular to the longitudinal axis of the beam developed from the edges to the transversal centre of the beam with roughly equal spacing of 100 mm in the range of displacement transducers.

[Side of RC beam]

- Several vertical cracks developed at the upper part of the beam with roughly equal spacing of 100 mm in the range of displacement transducers.

10 cycles:

[Top surface of RC beam]

- A medium-length crack almost perpendicular to the longitudinal axis of the beam developed at outside of G1 zone. Existing cracks increased those lengths.

[Side of RC beam]

- A short vertical crack appeared at outside of G1 zone. Existing cracks increased those lengths.

187 cycles:

[Top surface of RC beam]

- Existing cracks increased those length; especially, cracks at G3 and G5 zones extended significantly.

[Side of RC beam]

- Existing cracks increased those length; especially, cracks at G5 zones extended largely.

1,194 cycles:

[Top surface of RC beam]

- Two long curved cracks developed at outside of G7 zone from the edge to the transversal centre of the beam. Significant change wasn't observed on existing cracks.

[Side of RC beam]

- A short crack appeared at top of the beam at outside of G7 zone. Significant change wasn't observed on existing cracks.

10,410 cycles:

[Top surface of RC beam]

- Significant change wasn't observed on existing cracks.

[Side of RC beam]

- An existing short crack at outside of G7 zone propagated significantly. Significant change wasn't observed on the other existing cracks.

100,481 cycles:

[Top surface of RC beam]

- A curved crack at outside of G7 zone increased its length. Significant change wasn't observed on the other existing cracks.

[Side of RC beam]

- Significant change wasn't observed on existing cracks.

Failure (359,340 cycles):

[Top surface of RC beam]

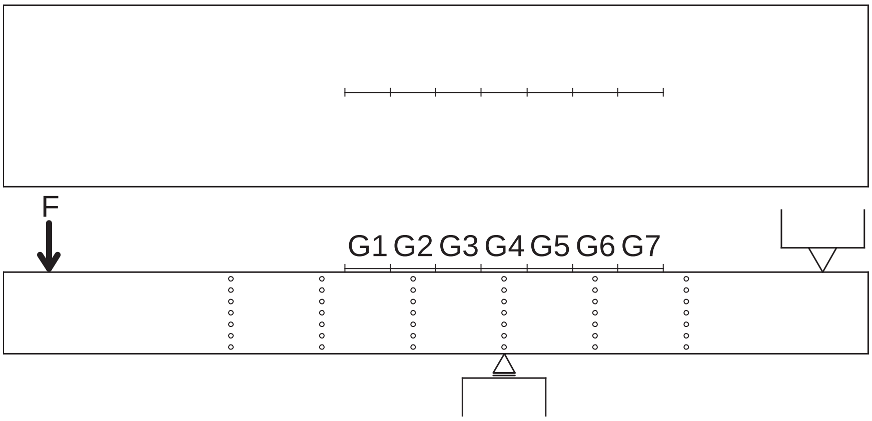
- A fracture crack appeared at G3 zone. Most part of the fracture crack newly developed.
- Several cracks were intensively caused at G3 zone.
- A few cracks approximately parallel to the longitudinal axisn of the beam developed more or less above a top steel rebar at an edge of the beam.

[Side of RC beam]

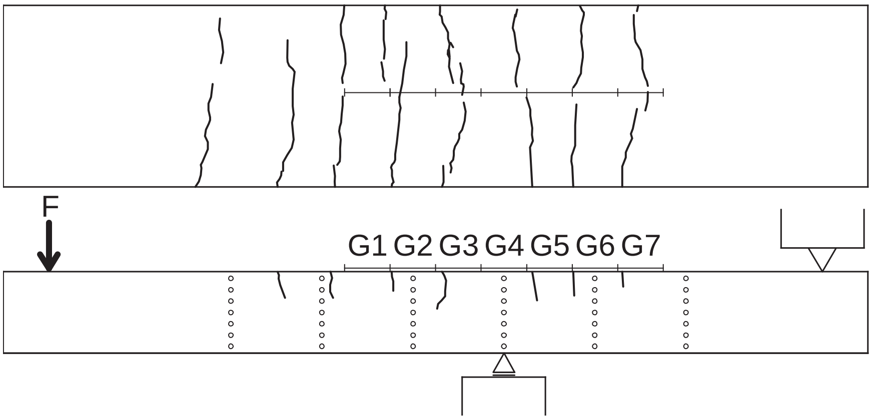
- A vertical fracture crack appeared at G3 zone on an existing crack.
- A vertical crack and crack slightly inclined from the vertical axis were caused at G3 and G4 zones respectively.
- A horizontal crack appeared approximately at the position of bottom steel rebars of the RC part at G2 zone.
- Concrete close to bottom fibre crushed at G3 zone.

Evolution of crack pattern on RC test specimen

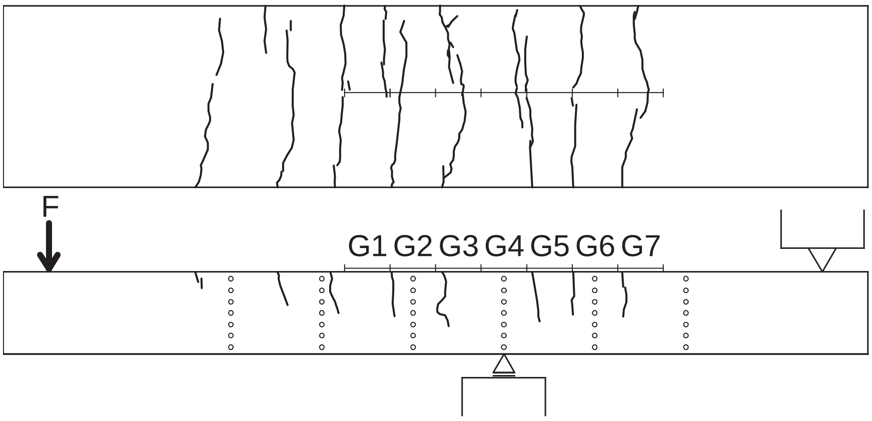
0 cycle



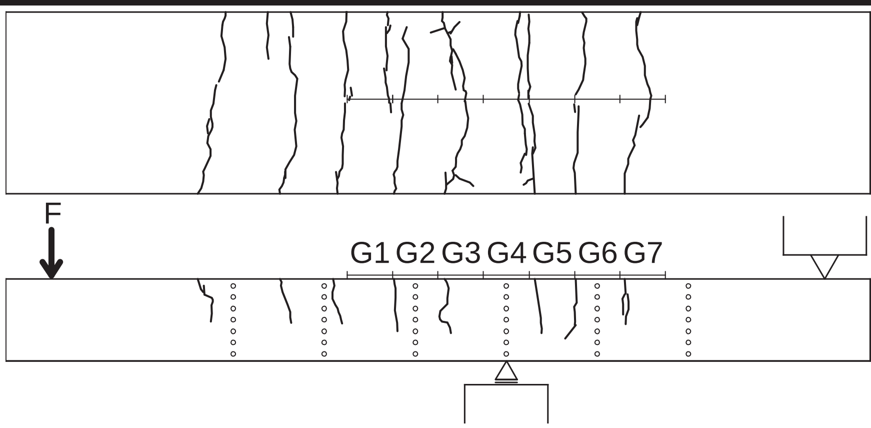
2 cycles



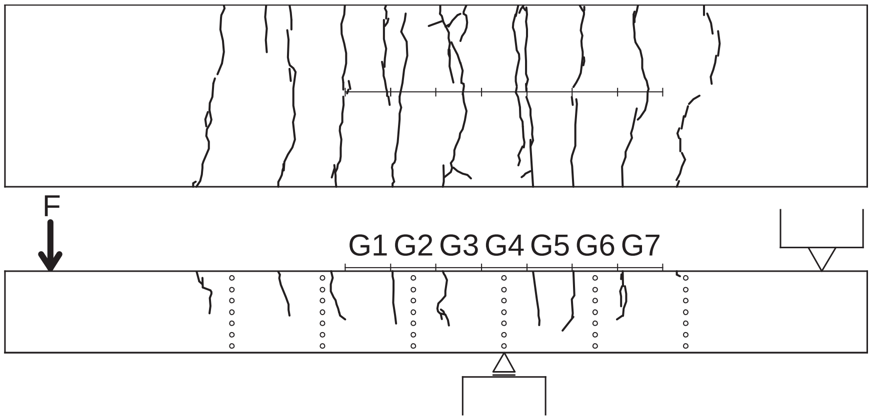
10 cycles



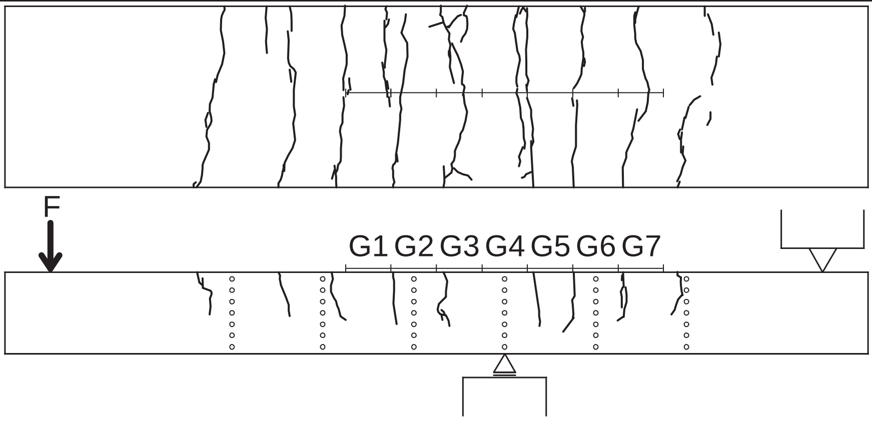
187 cycles



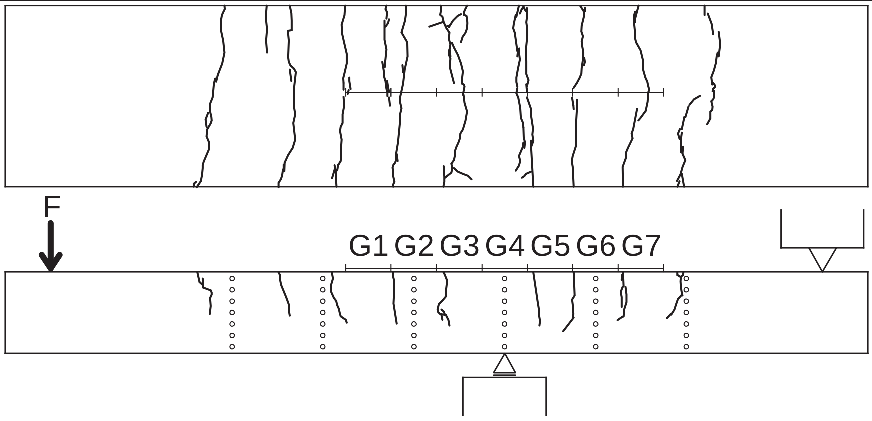
1,194 cycles



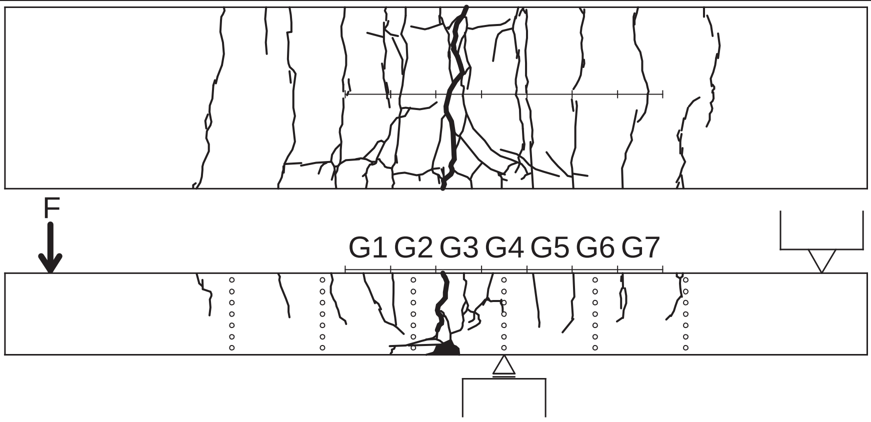
10,410 cycles



100,481 cycles



Failure (359,340 cycles)



6 Conclusion

This report presents the tests results of an experimental campaign carried out by the author to investigate the bending fatigue behaviour of RU-RC member. The results were used to draw an *S-N* diagram to determine the fatigue endurance limit and develop a model to predict the results. For discussion and analysis of the results, refer to the papers or the thesis of the author.

The following conclusions were drawn:

1) Deformation of the R-UHPFRC layer significantly grew in the beginning of the fatigue test, followed by moderate growth.

2) The distribution of deformation of the R-UHPFRC layer did not follow the distribution of acting bending moment on the RU-RC beam. This might be explained by local variations of material properties of UHPFRC.

3) Steel rebars in the R-UHPFRC layer fractured one by one almost at the same cross section causing one fracture plane in the R-UHPFRC layer.

4) Each time one of the four steel rebars in the R-UHPFRC layer fractured, behaviours of deflection of the RU-RC beam and deformation of the R-UHPFRC layer changed.

5) In all specimens, fracture crack in the R-UHPFRC layer propagated in a path approximately perpendicular to the longitudinal direction of the RU-RC beam.

6) After all the four steel rebars in the R-UHPFRC layer fractured, test-set up became unstable.

7 Reference

[1] Schläfli M., (1999) "Ermüdung von Brückenfahrbahnplatten aus Stahlbeton", Doctoral thesis No. 1998, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland